US012392614B2

(12) **United States Patent**
Inoue et al.

(10) **Patent No.: US 12,392,614 B2**
(45) **Date of Patent: *Aug. 19, 2025**

(54) **INERTIAL SENSOR, ATOMIC INTERFEROMETER, METHOD FOR ADJUSTING SPEEDS OF ATOMS, AND APPARATUS FOR ADJUSTING SPEEDS OF ATOMS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 281 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **18/028,891**

(22) PCT Filed: **Jul. 12, 2021**

(86) PCT No.: **PCT/JP2021/026165**

§ 371 (c)(1),
(2) Date: **Mar. 28, 2023**

(87) PCT Pub. No.: **WO2022/074891**

PCT Pub. Date: **Apr. 14, 2022**

(65) **Prior Publication Data**

US 2023/0332895 A1 Oct. 19, 2023

(30) **Foreign Application Priority Data**

Oct. 8, 2020 (JP) 2020-170504

(51) **Int. Cl.**
G01C 21/16 (2006.01)
G01C 19/62 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G01C 21/165*** (2013.01); ***G01C 19/62*** (2013.01); ***G01P 15/093*** (2013.01); ***G01P 15/18*** (2013.01)

(58) **Field of Classification Search**
CPC G01C 21/165; G01C 19/62; G01C 19/58; G01P 15/093; G01P 15/18; G01P 15/08
See application file for complete search history.

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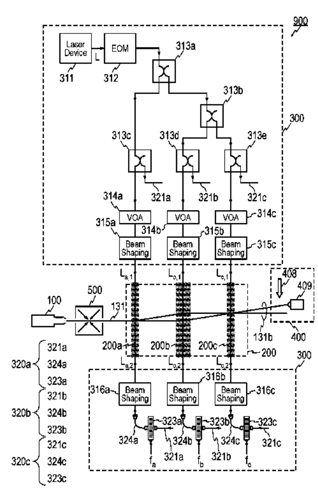
(74) *Attorney, Agent, or Firm* — Greenblum & Bernstein, P.L.C.

(57) **ABSTRACT**

An adjuster performs simultaneous irradiation of M laser beams to an atomic beam, where M is a predetermined integer satisfying 3≤M. The course of each of the M laser beams intersects with the course of the atomic beam. A component, in a direction perpendicular to the course of the atomic beam, of the sum of radiation pressure vectors that the M laser beams respectively have is zero. A component, in a direction of the course of the atomic beam, of the sum of the radiation pressure vectors that the M laser beams
(Continued)



respectively have is negative for atoms having speeds greater than a predetermined speed, and positive for atoms having speeds smaller than the predetermined speed.

25 Claims, 11 Drawing Sheets

(51) **Int. Cl.**
G01P 15/093 (2006.01)
G01P 15/18 (2013.01)

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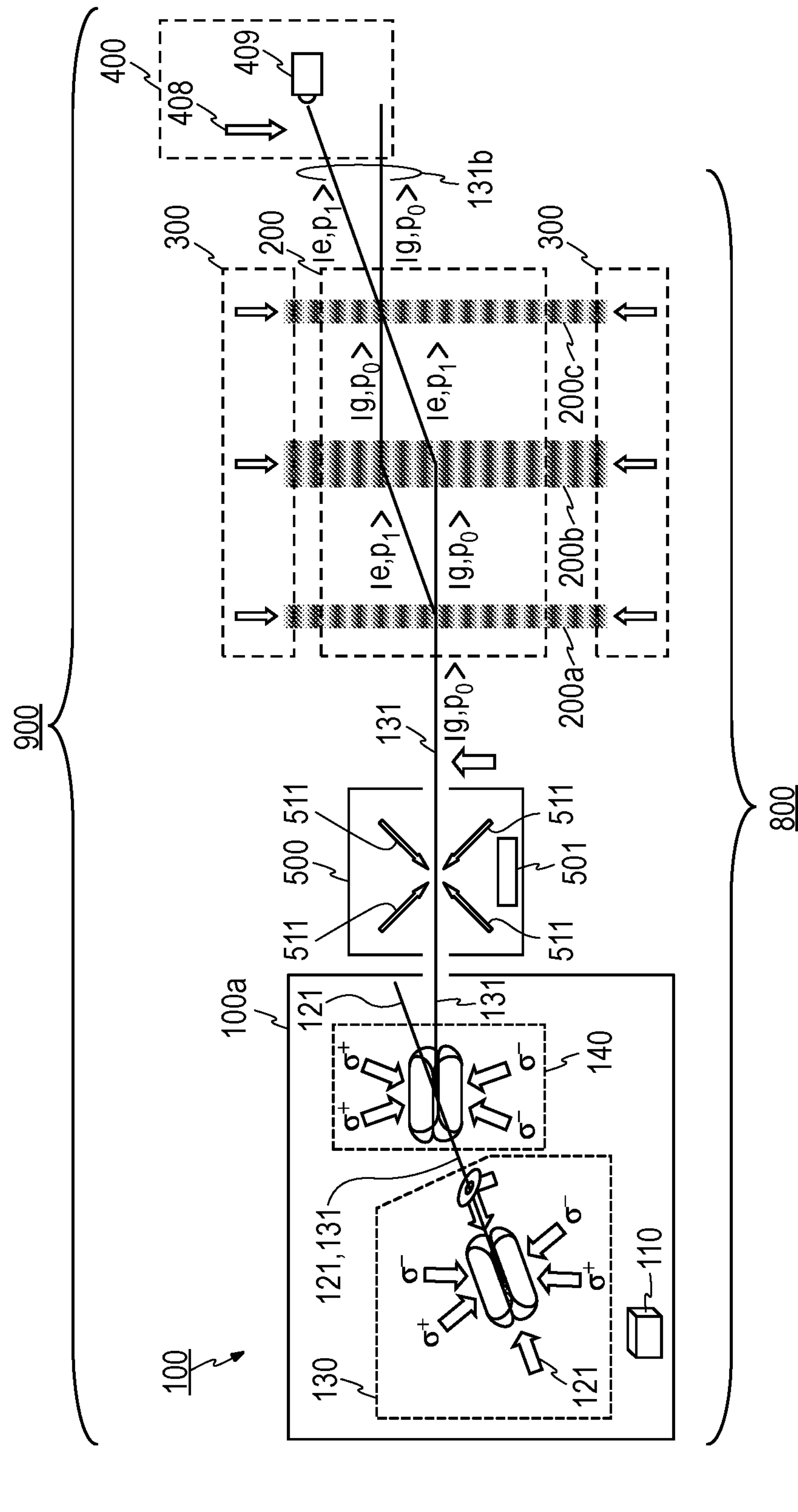

900
800
100
100a
110
121
121,131
130
131
131b
140
200
200a
200b
200c
300
400
408
409
500
501
511
|g,p$_0$>
|e,p$_1$>
σ$^+$
σ$^-$

FIG. 1

FIG. 2

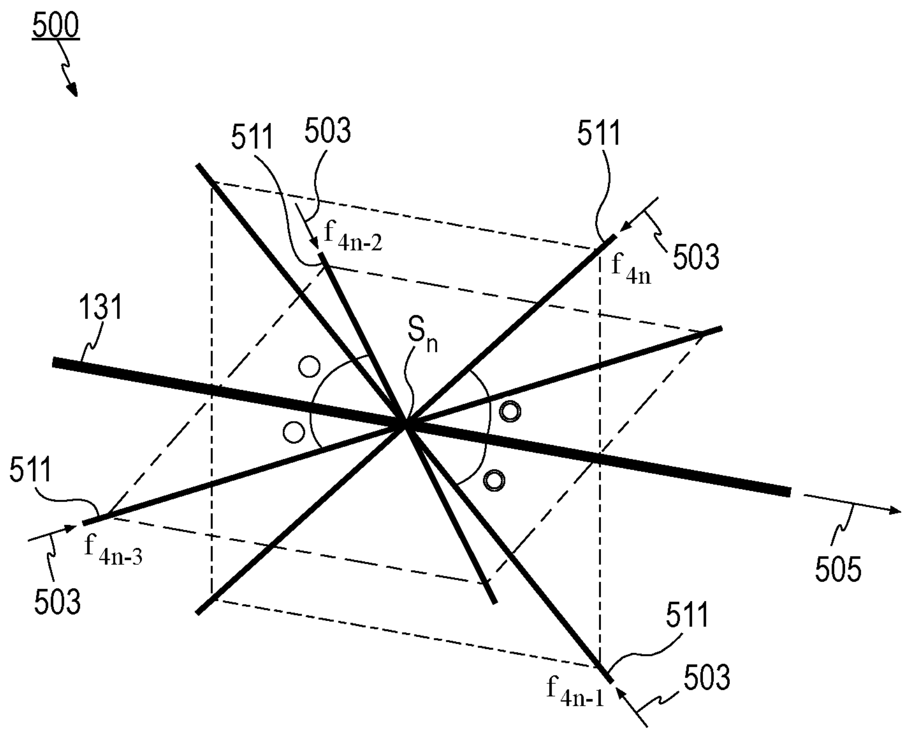

500
511
503
511
503
f_{4n-2}
f_{4n}
131
S_n
511
f_{4n-3}
503
505
511
503
f_{4n-1}

FIG. 3

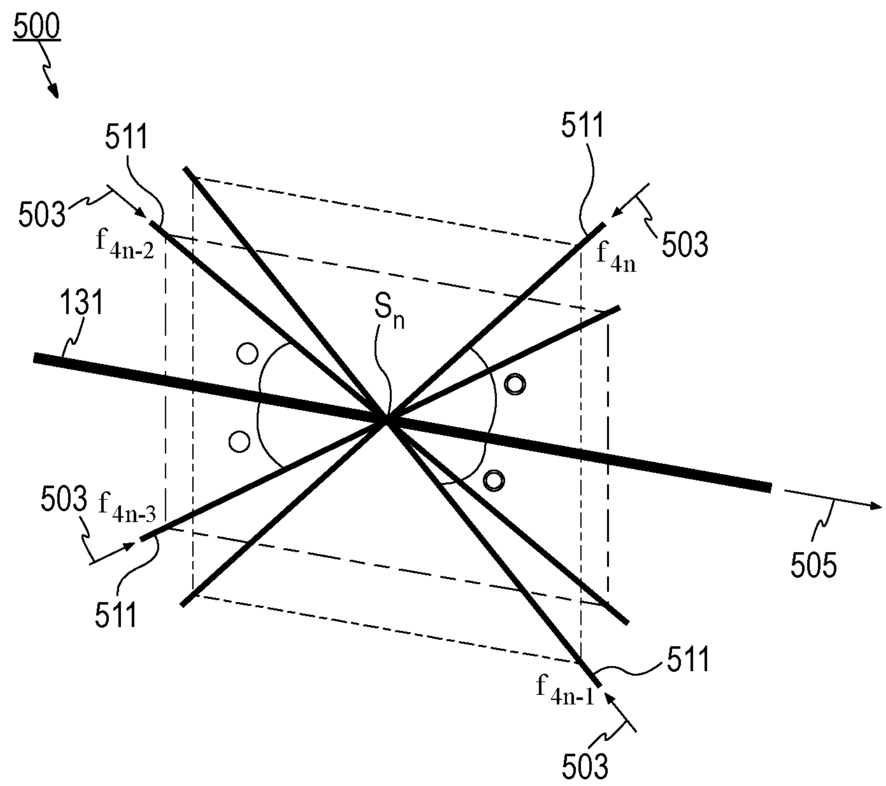
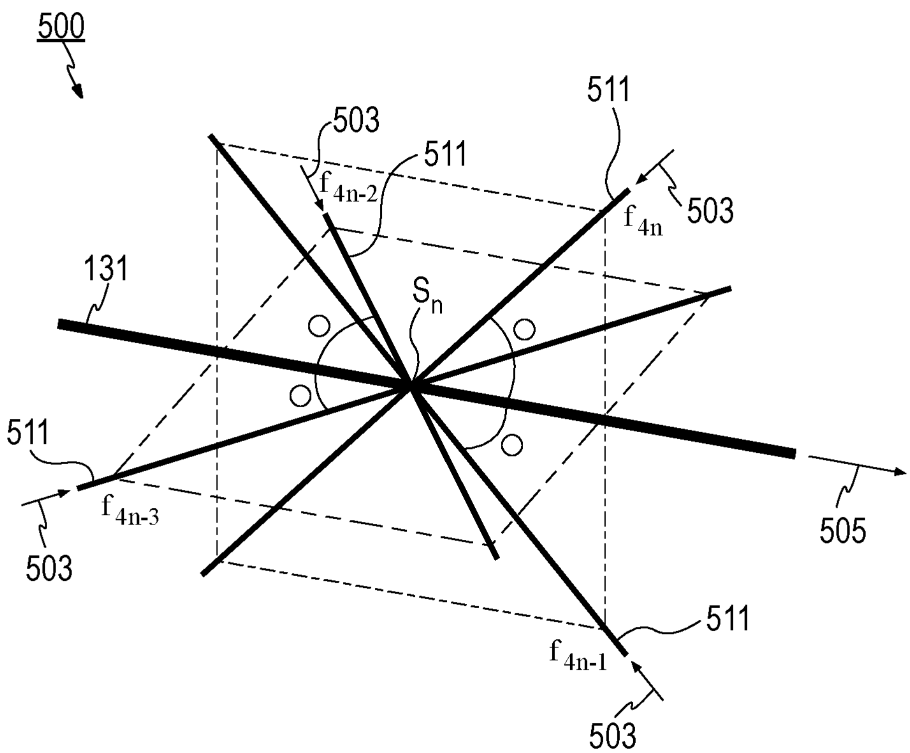

500
511
503
f_{4n-2}
511
503
f_{4n}
131
S_n
503
f_{4n-3}
511
505
511
f_{4n-1}
503

FIG. 4



500
503
511
f_{4n-2}
511
f_{4n}
503
131
S_n
511
f_{4n-3}
503
505
511
f_{4n-1}
503

FIG. 5

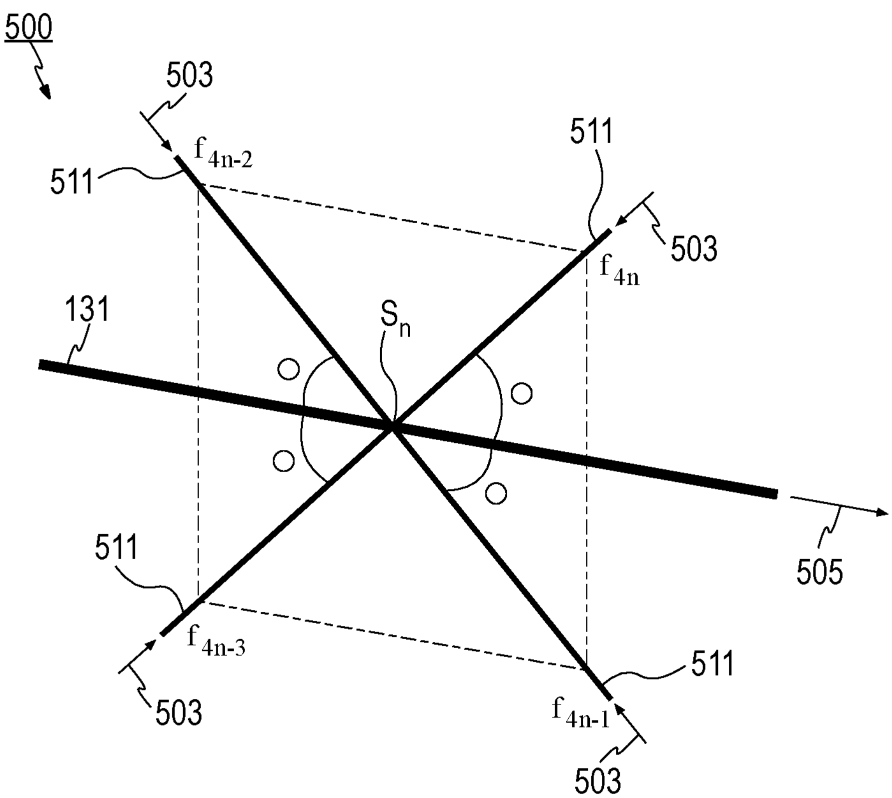

500
503
511
f_{4n-2}
511
503
f_{4n}
131
S_n
505
511
f_{4n-3}
503
511
f_{4n-1}
503

FIG. 6

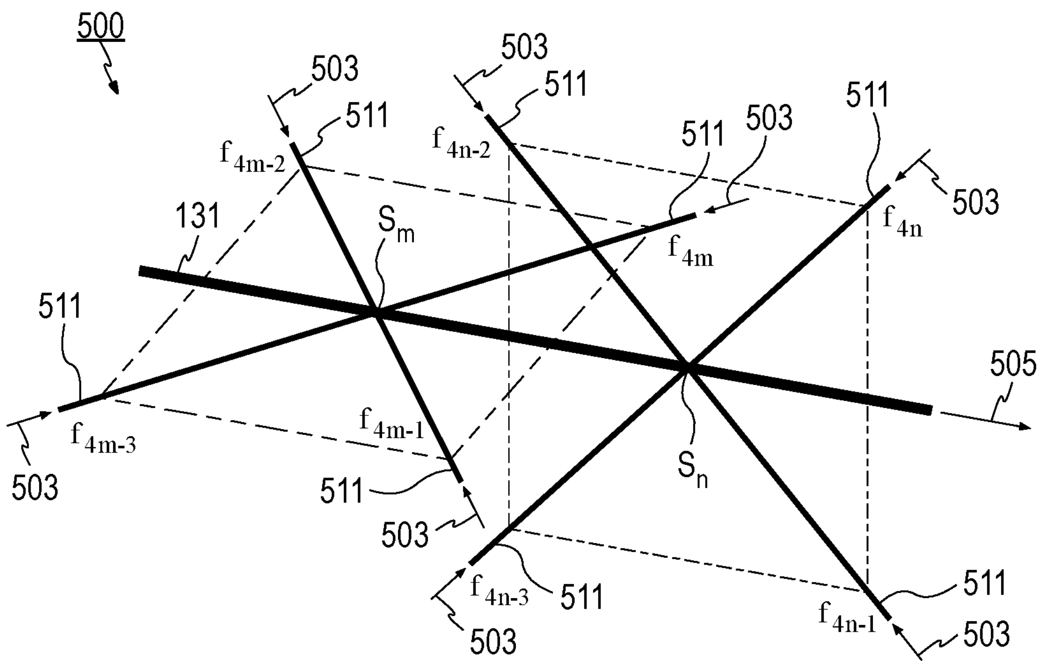


FIG. 7

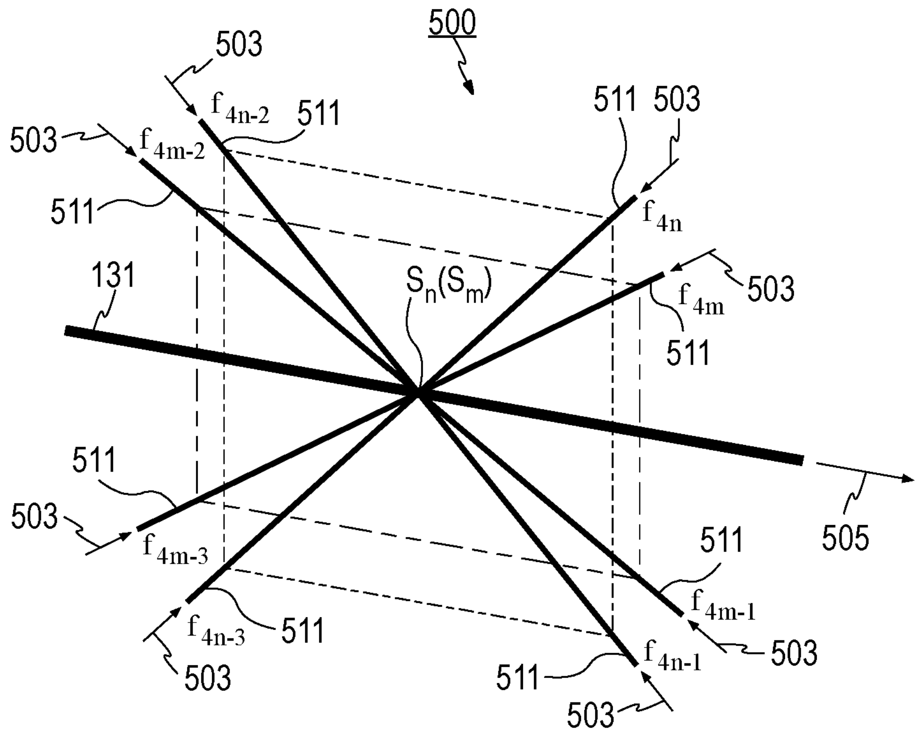


FIG. 8

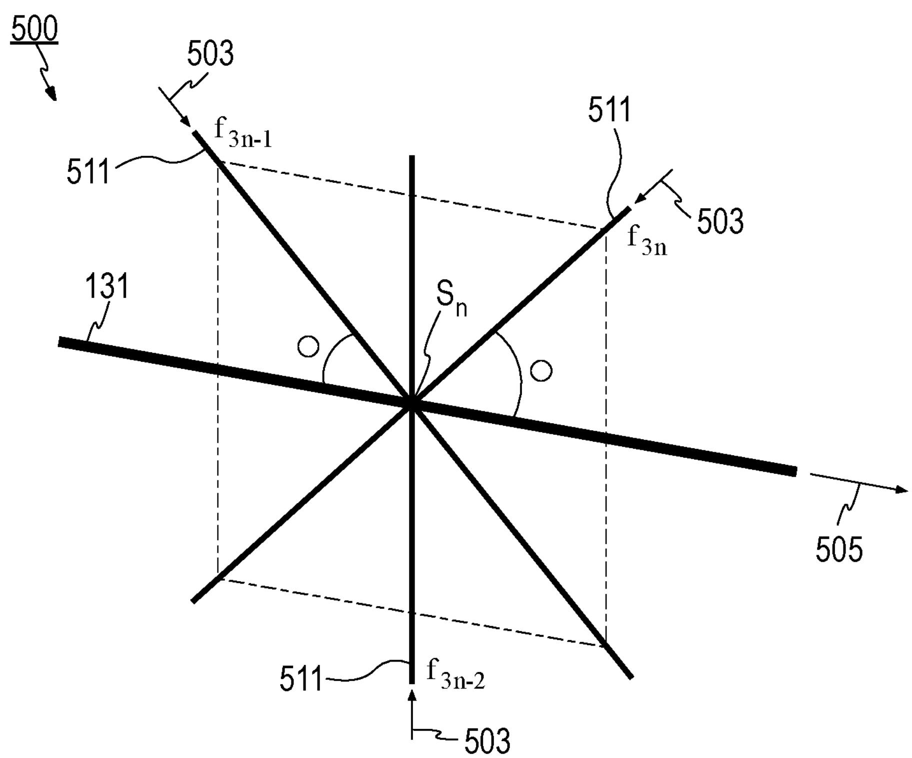
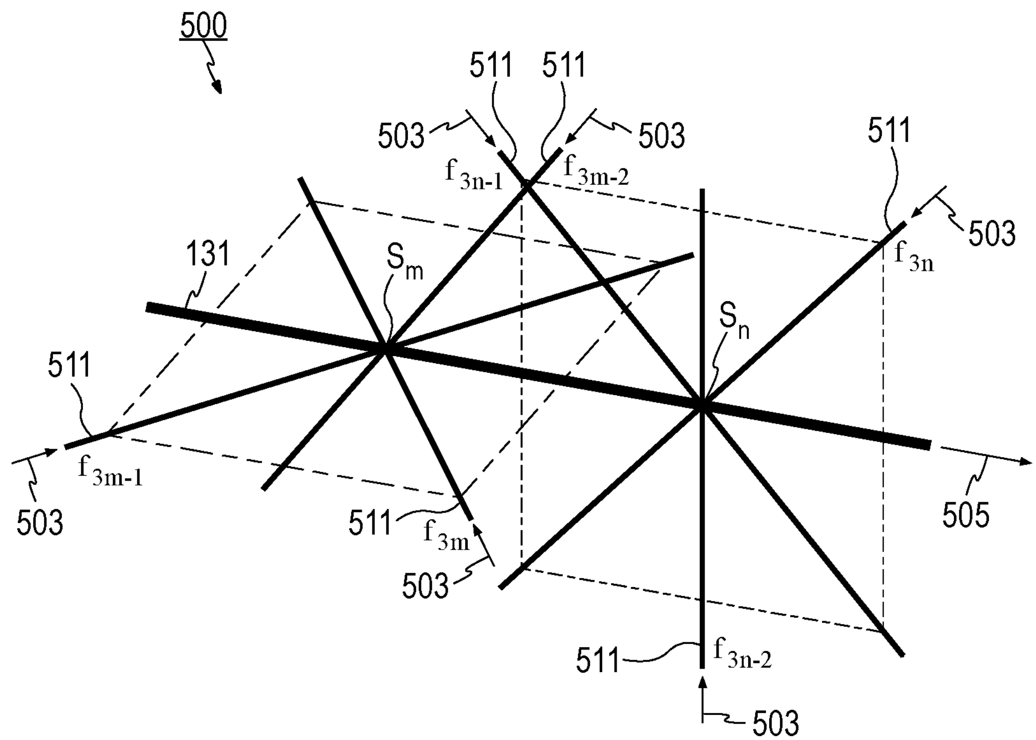


FIG. 9


500
511
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503
503
f_{3n-1}
f_{3m-2}
511
503
f_{3n}
131
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S_n
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f_{3m-1}
503
511
f_{3m}
503
505
511
f_{3n-2}
503

FIG. 10

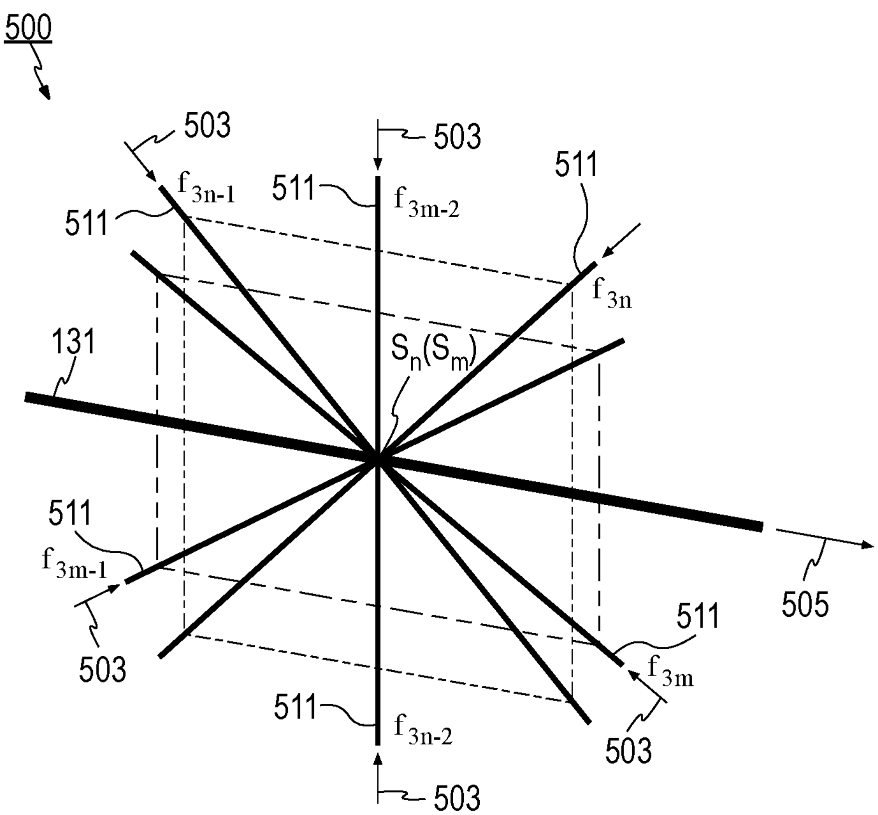
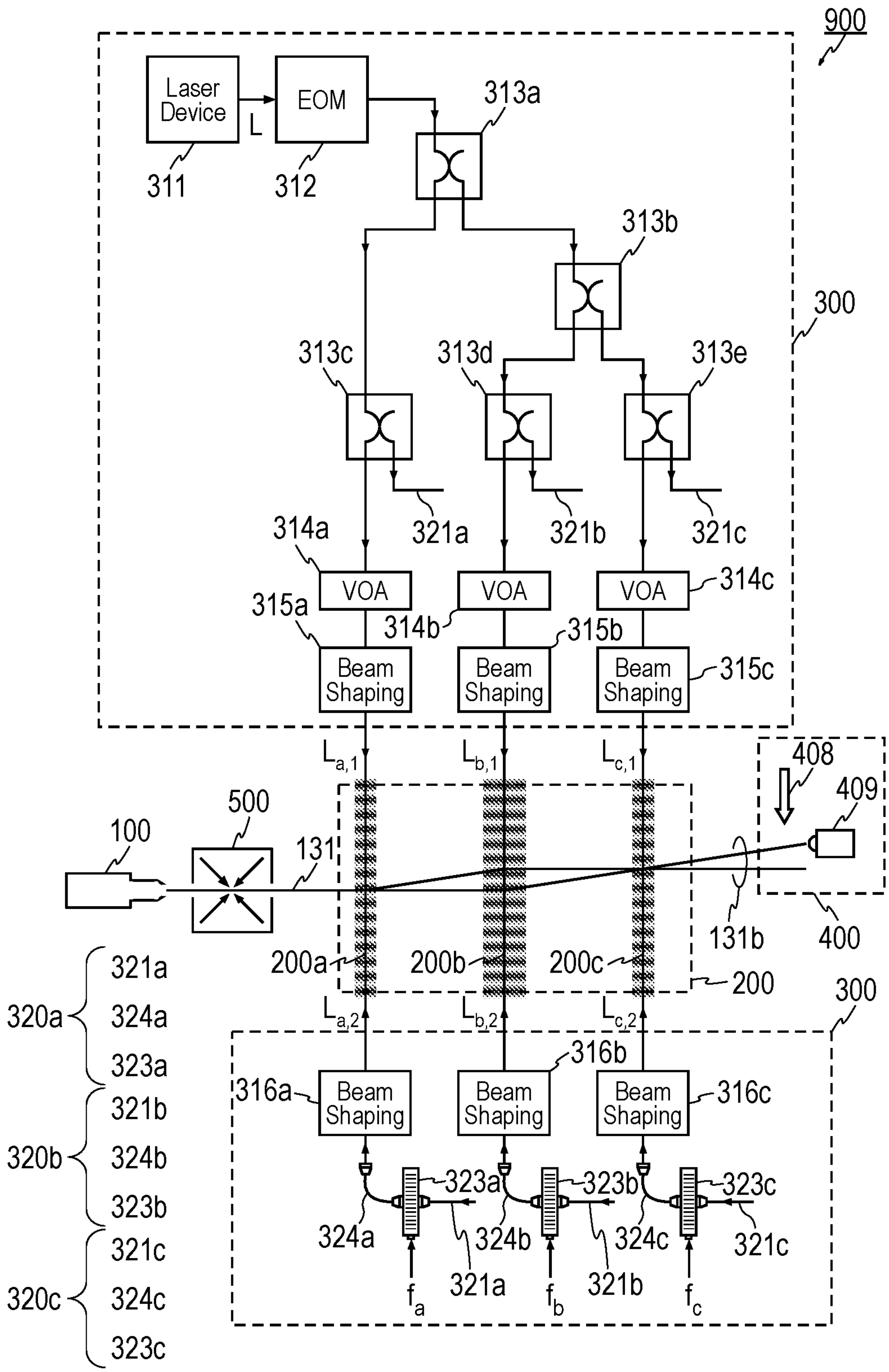

500
503
503
511
f3n-1
511
f3m-2
511
f3n
511
131
Sn(Sm)
511
f3m-1
503
505
511
f3m
511
f3n-2
503
503

FIG. 11


900
Laser Device
EOM
L
311
312
313a
313b
313c
313d
313e
300
321a
321b
321c
314a
314b
314c
VOA
VOA
VOA
315a
315b
315c
Beam Shaping
Beam Shaping
Beam Shaping
$L_{a,1}$
$L_{b,1}$
$L_{c,1}$
408
409
100
500
131
131b
400
200a
200b
200c
200
$L_{a,2}$
$L_{b,2}$
$L_{c,2}$
300
316a
316b
316c
Beam Shaping
Beam Shaping
Beam Shaping
323a
323b
323c
324a
324b
324c
321a
321b
321c
f_a
f_b
f_c
320a
321a
324a
323a
320b
321b
324b
323b
320c
321c
324c
323c

INERTIAL SENSOR, ATOMIC INTERFEROMETER, METHOD FOR ADJUSTING SPEEDS OF ATOMS, AND APPARATUS FOR ADJUSTING SPEEDS OF ATOMS

TECHNICAL FIELD

The present invention relates to an adjustment technique for making the speeds of atoms contained in an atomic beam close to a predetermined speed, and an atomic interference technique using the adjustment technique.

BACKGROUND ART

In recent years, with the advancement of laser technology, studies have been progressing on atomic interferometers, inertial sensors using atomic interference, etc. Examples of such atomic interferometers include a Mach-Zehnder atomic interferometer and a Ramsey-Bordé atomic interferometer (see, for example, Non-patent literature 1).

In the basic scheme of the Mach-Zehnder atomic interferometer, an atomic beam is irradiated with two moving standing light waves called $\pi/2$ pulses and one moving standing light wave called π pulse. The interaction between the atomic beam and the moving standing light waves splits the atomic beam into two atomic beams, and further the two atomic beams intersect with each other. As a result, obtained is an atomic beam corresponding to the superposition state of an atomic state corresponding to one of the two atomic beams and an atomic state corresponding to the other atomic beam.

For example, when a Mach-Zehnder atomic interferometer receives an angular velocity within a plane containing two atomic beams of the Mach-Zehnder atomic interferometer, a phase difference occurs between the two atomic beams, and this phase difference is reflected to the existence probability of the atomic state corresponding to one of the two atomic beams and the existence probability of the atomic state corresponding to the other atomic beam. Therefore, the angular velocity can be detected by observing the atomic beam corresponding to the superposition state of the atomic state corresponding to one of the two atomic beams and the atomic state corresponding to the other atomic beam.

PRIOR ART LITERATURE

Non-Patent Literature

Non-patent literature 1: T. L. Gustavson, P. Bouyer and M. A. Kasevich, "Precision Rotation Measurements with an Atom Interferometer Gyroscope," Phys. Rev. Lett. 78, 2046-2049, Published 17 Mar. 1997.

SUMMARY OF THE INVENTION

Problems to be Solved by the Invention

An atomic beam to be irradiated with the moving standing light waves is preferably a cold atomic beam that has a low speed in the traveling direction of the atomic beam, a narrow speed spread in a direction perpendicular to the traveling direction of the atomic beam, and a high flux.

With respect to cold atomic beams, it is generally known that the distribution in speed of atoms in the traveling direction of a cold atomic beam has a width of about 20% of the mode thereof, and when the mode of this distribution is 20 m/s, for example, this distribution has a width of about ±2 m/s.

Therefore, the interaction time between each of atoms contained in the atomic beam and the moving standing light wave varies among the atoms. This non-uniformity in interaction time causes a decrease in the number of atoms contributing to interference, which causes reduction in contract between the state of atoms corresponding to one of the two atomic beams and the state of atoms corresponding to the other atomic beam, of atoms obtained from the atom interferometer.

Further, the difference in the population of atoms, the atoms being obtained from the atomic interferometer, between in the state corresponding to one of the two atomic beams and in the state corresponding to the other atomic beam is expressed by using a cosine function of phase dependent on the speeds of the atoms and the angular velocity applied to the atomic interferometer. When a sufficiently large angular velocity applied to the atom interferometer, atoms having various speeds within the width of the distribution in speed of atoms contribute to variation in the difference of the population as cosine functions of various phases, so that the cosine functions of the various phases cancel one another, and thereby the contrast is reduced. In other words, the width of the distribution in speed of atoms causes reduction in the dynamic range.

Therefore, it is desirable to reduce the width of the distribution in speed of atoms in the traveling direction of the cold atomic beam.

An object of the present invention is to provide an adjustment technique for making the speeds of atoms contained in an atomic beam close to a predetermined speed, and an atomic interferometer and an inertial sensor using the adjustment technique.

Means to Solve the Problems

Technical matters described in this section are neither intended to explicitly or implicitly limit inventions recited in the claims, nor intended to allow any person other than persons benefiting from the present inventions (for example, applicants and proprietors) to limit or construe in a limited sense the inventions recited in the claims, and are merely provided to facilitate understanding of the gist of the present invention. A general outline of the invention from other aspects can be appreciated, for example, from the claims as originally filed in the present patent application.

According to the adjustment technique disclosed herein, an atomic beam is simultaneously irradiated with M laser beams, where M represents a predetermined integer satisfying $3 \leq M$. The course of each of the M laser beams intersects with the course of the atomic beam. The M laser beams have their respective radiation pressure vectors and a component, in a direction perpendicular to the course of the atomic beam, of the sum of the radiation pressure vectors is zero. A component, in a direction of the course of the atomic beam, of the sum of the radiation pressure vectors is negative for atoms having speeds greater than a predetermined speed, and also positive for atoms having speeds smaller than the predetermined speed.

Each of an atomic interferometer and an inertial sensor includes this adjustment technique.

Effects of the Invention

According to the adjustment technique of the present invention, the speeds of the atoms contained in the atomic beam approach the predetermined speed. Also, according to the atom interferometer and inertial sensor of the present invention, the dynamic range is improved.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a configuration example of an atomic interferometer using an adjuster;

FIG. **2** is a configuration example of the adjuster;

FIG. **3** is a configuration example of the adjuster;

FIG. **4** is a configuration example of the adjuster;

FIG. **5** is a configuration example of the adjuster;

FIG. **6** is a configuration example of the adjuster;

FIG. **7** is a configuration example of the adjuster;

FIG. **8** is a configuration example of the adjuster;

FIG. **9** is a configuration example of the adjuster;

FIG. **10** is a configuration example of the adjuster; and

FIG. **11** is an optical configuration example of an interference unit.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Embodiments of the present invention will be described with reference to the drawings. Note that the drawings are for understanding the embodiments, and the dimensions of the illustrated component elements are different from actual dimensions.

An inertial sensor **900** including an exemplary Mach-Zehnder atomic interferometer **800** shown in FIG. **1** comprises a cold atomic beam generation apparatus **100** for continuously generating a cold atomic beam having a narrow speed spread in a direction perpendicular to a traveling direction of the cold atomic beam, an adjuster **500** for making the speeds of atoms contained in the cold atomic beam close to a predetermined speed, a moving standing light wave generator **300** for generating three moving standing light waves, an interference unit **200** for obtaining an atomic beam resulting from the interaction between the cold atomic beam from the adjuster **500** and the three moving standing light waves, and a monitor **400** for observing the atomic beam from the interference unit **200**. In the present embodiment, the cold atomic beam generation apparatus **100**, the adjuster **500**, the interference unit **200**, and the monitor **400** are housed in a vacuum chamber (not shown). The Mach-Zehnder atomic interferometer **800** has a configuration identical to that of the inertial sensor **900** except for the monitor **400**.

The cold atomic beam generation apparatus **100** may be, for example, a device disclosed in Reference literature 1. The cold atomic beam generation apparatus **100** comprises, in a partition **100*a*** of the vacuum chamber thereof, an atom source **110** for generating gaseous atoms, a cold atomic beam generator **130** for generating by using a pushing laser beam **121** a cold atomic beam **131** from the cloud of the gaseous atoms trapped in the space, and an atomic beam deflector **140** for bending the course of the cold atomic beam **131**. The cold atomic beam generator **130** has, for example, a 2D$^+$-MOT mechanism, and the atomic beam deflector **140** has, for example, a 2D-MOT mechanism.

(Reference literature 1) Japanese Patent Application Laid Open No. 2020-20636

The atom source **110** generates gaseous atoms. The atom source **110** has a configuration in which a solid is sublimated or a configuration in which a liquid evaporates or volatilizes. The solid or liquid preferably made from a highly pure single element. For example, in the case of using strontium or calcium, a heating device is required, but in the case of using rubidium or cesium, the saturated steam pressure at room temperature (a temperature suitable for human activity) is high (that is, it readily vaporizes), so that sufficient gaseous atoms can be obtained without use of a heating device.

The gaseous atoms (hereinafter simply referred to as atoms) filling the partition **100*a*** of the vacuum chamber are naturally supplied to the cold atomic beam generator **130** which is a 2D$^+$-MOT mechanism. In the 2D$^+$-MOT mechanism, as described later, the pushing laser beam **121** is used to generate the cold atomic beam **131** from the cold atom cloud trapped in the space inside coils, and furthermore, the pushing laser beam **121** leaks out in the traveling direction of the cold atomic beam **131**.

In view of the flux of the cold atomic beam **131** that can be achieved in light of the current technical level, the total number of collisions per unit time and unit volume between the atoms filling the partition **100*a*** of the vacuum chamber and the cold atomic beam **131** is sufficiently small (i.e., the mean free path is long).

To give a simple example, the 2D$^+$-MOT mechanism includes coils (for example, Ioffe coils) for forming a two-dimensional quadrupole magnetic field, and three pairs of laser beams which are arranged in accordance with three axes of symmetry of the two-dimensional quadrupole magnetic field. In the 2D$^+$-MOT mechanism, the three pairs of laser beams apply a damping force to each atom according to the velocity of the atom (to form an optical molasses), and additionally the radiation pressure difference of each laser beam pair, which is caused by the Zeeman shift according to the position of the atom due to the two-dimensional quadrupole magnetic field and the transition selection rule in each laser beam pair, applies a damping force (for example, a force toward the zero magnetic field line of the two-dimensional quadrupole magnetic field) to each atom according to the position of the atom, resulting in generation of a cold atom cloud of atoms trapped in a space.

Each of two laser beam pairs out of the three laser beam pairs is a pair of circularly polarized light σ^+ and circularly polarized light σ^- (where σ^- corresponding to σ^+ is formed by reflecting σ^+ with a reflective quarter-wave plate) that travel in opposition to each other and also have the same frequency (specifically, a frequency slightly lower than the resonant frequency of the atom). The two laser beam pairs orthogonally intersect each other (specifically, the course of σ^+ for example in one of the laser beam pairs orthogonally intersects the course of σ^+ for example in the other laser beam pair), and furthermore, each of the two laser beam pairs intersects the zero magnetic field line of the two-dimensional quadrupole magnetic field formed by the coils. Each of the two laser beam pairs laser-cools, in a direction orthogonal to the zero magnetic field line, atoms existing in the space inside the 2D$^+$-MOT mechanism.

The remaining laser beam pair among the three laser beam pairs is a pair of circularly polarized light σ^+ and circularly polarized light σ^- that travel in opposition to each other on the zero magnetic field line of the two-dimensional quadrupole magnetic field and also have the same frequency (specifically, a frequency slightly lower than the resonant frequency of the atom). The laser beam pair laser-cools, in the direction of the zero magnetic field line, atoms existing in the space inside the 2D$^+$-MOT mechanism. The beam intensity of one of the laser beams forming the laser beam pair is set stronger than the beam intensity of the other laser beam. The other laser beam is introduced into the space inside the coils using a perforated reflective plate disposed at a 45-degree angle with respect to the direction of the zero magnetic field line, and therefore the other laser light includes a "shadow (that is, dark part) in the direction of the zero magnetic field line" corresponding to the hole in the perforated reflective plate. Consequently, one of the laser beams effectively acts as the pushing laser beam **121** due to the beam intensity difference and the asymmetric scattering rates, and the cold atomic beam **131** is drawn out through the perforated reflective plate from the cold atom cloud trapped near the zero magnetic field line. As described above, one of the laser beams (effectively the pushing laser beam) leaks out together with the cold atomic beam **131** from the hole in the perforated reflective plate.

To give a simple example, the 2D-MOT mechanism has a configuration such that one laser beam pair on the zero magnetic field line of the two-dimensional quadrupole magnetic field is excluded from the $2D^+$-MOT mechanism.

In such a cold atomic beam generation apparatus **100**, the course of the cold atomic beam **131** from the cold atomic beam generator **130** (this course matches the zero magnetic field line of the two-dimensional quadrupole magnetic field) matches the course of the pushing laser beam **121** (that is, one of the laser beams constituting one laser beam pair on the zero magnetic field line of the two-dimensional quadrupole magnetic field).

The cold atomic beam generator **130** and the atomic beam deflector **140** have a positional relationship such that the zero magnetic field line of the quadrupole magnetic field in the 2D-MOT mechanism of the atomic beam deflector **140** intersects with the course of the cold atomic beam **131** from the cold atomic beam generator **130** (that is, the zero magnetic field line of the two-dimensional quadrupole magnetic field in the $2D^+$-MOT mechanism). The intersection angle between the direction of the zero magnetic field line of the quadrupole magnetic field in the 2D-MOT mechanism and the direction of the zero magnetic field line of the two-dimensional quadrupole magnetic field in the $2D^+$-MOT mechanism is determined according to factors such as design conditions, but it is set to a predetermined angle that satisfies 5 degrees or more and 60 degrees or less, for example.

The cold atomic beam **131** and the leaking pushing laser beam **121** enter the atomic beam deflector **140** having a configuration that includes the 2D-MOT mechanism. From the above-described positional relationship between the cold atomic beam generator **130** and the atomic beam deflector **140**, the cold atomic beam **131** and the leaking pushing laser beam **121** obliquely cross the zero magnetic field line of the quadrupole magnetic field in the 2D-MOT mechanism of the atomic beam deflector **140**. The damping force according to the velocity and position of each atom is applied to each atom through the 2D-MOT mechanism and the traveling direction of the cold atomic beam **131** is thereby changed to the direction of the zero magnetic field line of the quadrupole magnetic field in the 2D-MOT mechanism. However, the pushing laser beam **121** is unaffected by the 2D-MOT mechanism, and therefore the traveling direction of the pushing laser beam **121** is unchanged. Consequently, the atomic beam deflector **140** causes the cold atomic beam **131** to travel in a direction different from the traveling direction of the pushing laser beam **121**.

The cold atomic beam **131** from the atomic beam deflector **140** is a cold atomic beam which has a low speed in the traveling direction of the atomic beam, a narrow speed spread in a direction perpendicular to the traveling direction of the atomic beam, and a high flux.

The cold atomic beam **131** from the atomic beam deflector **140** enters the adjuster **500**. The pushing laser beam **121** traveling in a direction different from the traveling direction of the cold atomic beam **131** is terminated appropriately and does not enter the adjuster **500**.

The adjuster **500** utilizes simultaneous irradiation of laser beams to make the speeds of atoms contained in the cold atomic beam **131** close to a predetermined speed. The adjuster **500** includes a laser beam generator **501** for generating M laser beams **511**. M represents a predetermined integer satisfying $3 \le M$. The total number M of laser beams **511** is the number of laser beams **511** which are visible from atoms to be irradiated with the laser beams **511**, and does not necessarily match the number of laser light sources.

The laser beam generator **501** generates M laser beams **511** satisfying the following conditions.

(1) The course **503** of each of the M laser beams **511** intersects with the course **505** of the cold atomic beam **131**.

(a) A component, in a direction perpendicular to the course **505** of the cold atomic beam **131**, of the sum of the radiation pressure vectors that the M laser beams **511** respectively have is zero.

(b) A component, in a direction of the course **505** of the cold atomic beam **131**, of the sum of the radiation pressure vectors that the M laser beams **511** respectively have is negative for atoms having speeds greater than a predetermined speed v_d, and positive for atoms having speeds smaller than the predetermined speed v_d.

The condition (1) indicates that the positional relationship between the course **503** of each of the M laser beams **511** and the course **505** of the cold atomic beam **131** is neither a parallel positional relationship (where "parallel" includes a case where both the courses match each other) nor a torsional positional relationship, and this condition is a condition for preventing the laser beams **511** used in the adjuster **500** from adversely affecting the interference system of the interference unit **200** described later and for causing the laser beam **511** to act on the atoms contained in the cold atomic beam **131**. The courses **503** and the course **505** are respectively the courses of the laser beams **511** and the course of the cold atomic beam **131** immediately before they intersect with each other. The conditions (a) and (b) will be described later.

The laser beam generator **501** may generate the M laser beams **511** further satisfying the following condition.

(2) The M laser beams **511** are mutually superposed in one predetermined spatial region through which the cold atomic beam **131** passes.

The condition (2) is a condition for simultaneously inducing interactions between the atoms and the M laser beams **511**, and contributes to achievement of a compact adjuster **500**.

The conditions (a) and (b) will be described. When j represents each integer satisfying $1 \le j \le M$, k_j represents the wave vector of a j-th laser beam **511**, and I_j represents the intensity of the j-th laser beam **511**, an average radiation pressure vector F_j of the j-th laser beam **511** to act on an atom moving at a velocity v is given by Formula (1). The laser beam **511** is a plane wave, h represents the Planck's constant, F represents the natural width of the transition, I_{sat} represents the saturation intensity of the transition, $\delta_j - k_j \cdot v$ represents detuning from a resonance frequency f_0 in consideration of the Doppler effect, and the speed $|v|$ is sufficiently smaller than the speed of light c.

[Formula 1]

$$F_j = \frac{1}{2}\frac{I_j/I_{sat}}{1 + I_j/I_{sat} + (\delta_j - k_j \cdot v)^2/(\Gamma/2)^2}(2\pi\Gamma)hk_j \tag{1}$$

When $(I_j/I_{sat})/(1+(\delta_j-_k\cdot v)^2/(\Gamma^2/4))$ is small, the radiation pressure vector F which an atom receives from the M laser beams **511** is given as the sum of M average radiation pressure vectors F_j, so that the conditions (a) and (b) are expressed by formulas (2) and (3), respectively. Here, a in Formula (3) is a positive constant, and e_v represents the direction of the course **505** of the cold atomic beam **131**, in other words, e_v is a unit direction vector in the moving direction of an atom moving at a velocity v.

[Formula 2]

$$F_{\perp v} = \sum_{j=1}^{M}(F_j)_{\perp v} \simeq 0 \tag{2}$$

$$F_{\parallel v} = \sum_{j=1}^{M}(F_j)_{\parallel v} = -a(|v| - v_d)e_v(a > 0) \tag{3}$$

The condition (a) is a condition for preventing the irradiation of the M laser beams **511** from imparting momentum to an atom in the direction perpendicular to the course **505** of the cold atomic beam **131**. The condition (b) is a condition for depriving by irradiation of the M laser beams **511** momentum from an atom having a speed greater than a predetermined speed v_d in the direction of the course **505** of the cold atomic beam **131**, that is, in the traveling direction of the cold atomic beam **131**, and for giving by irradiation of the M laser beams **511** momentum to an atom having a speed smaller than the predetermined speed v_d in the direction of the course **505** of the cold atomic beam **131**.

The conditions (a) and (b) or the Formulas (2) and (3) are satisfied by appropriately setting the intensity I_j of the laser beam **511**, and the detuning $\delta_j-k_j\cdot v$ from the resonance frequency f_0 in consideration of the Doppler effect, that is, the course **503** of the laser beam **511** and the frequency f_j of the laser beam **511**.

With a configuration satisfying at least the conditions (1), (a), and (b), when the speed of an atom in the traveling direction of the cold atomic beam **131** is greater than a predetermined speed, the atom is decelerated in the traveling direction of the cold atomic beam **131**, and when the speed of an atom in the traveling direction of the cold atomic beam **131** is smaller than the predetermined speed, the atom is accelerated in the traveling direction of the cold atomic beam **131**. Accordingly, the speeds of atoms in the traveling direction of the cold atomic beam **131** approach a predetermined speed.

An example of the configuration satisfying the above conditions (1), (a), and (b) will be described. Assuming that the speed |v| is sufficiently smaller than the speed of light c, that is, Formula (4) is assumed for each j and further higher-order terms of a minute amount e are ignored, a first-order approximation of Formula (1) is given by Formula (5).

[Formula 3]

$$e = \frac{|2\delta_j k_j \cdot v|}{\delta_j^2 + (1 + I_j/I_{sat})(\Gamma/2)^2} \ll 1 \tag{4}$$

$$F_j \simeq \frac{1}{2}\frac{I_j/I_{sat}}{1 + I_j/I_{sat} + \delta_j^2/(\Gamma/2)^2}(2\pi\Gamma)hk_j + \frac{1}{2}\frac{2I_j/I_{sat}}{(\Gamma/2)^2(1 + I_j/I_{sat} + \delta_j^2/(\Gamma/2)^2)^2}(2\pi\Gamma)h\delta_j(k_j \cdot v)k_j \tag{5}$$

Therefore, in the case of $\delta_j=\delta$ and $I_j=I$ for any j, Formula (6) holds.

[Formual 4]

$$\sum_{j=1}^{M}F_j \simeq \frac{1}{2}\frac{I/I_{sat}}{1 + I/I_{sat} + \delta^2/(\Gamma/2)^2}(2\pi\Gamma)h\sum_{j=1}^{M}k_j + \frac{1}{2}\frac{2I/I_{sat}}{(\Gamma/2)^2(1 + I/I_{sat} + \delta^2/(\Gamma/2)^2)^2}(2\pi\Gamma)h\delta\sum_{j=1}^{M}(k_j \cdot v)k_j \tag{6}$$

Here, when the condition of Formula (7) is satisfied, Formulas (8) and (9) hold with respect to Formula (6). Here, e_j is a unit direction vector in a direction perpendicular to the unit direction vector e_v on a plane containing the unit direction vector e_v and the wave vector k_j.

[Formula 5]

$$\sum_{j=1}^{M}k_j = 0 \tag{7}$$

$$\sum_{j=1}^{M}(F_j)_{\perp v} \simeq \frac{1}{2}\frac{2I/I_{sat}}{(\Gamma/2)^2(1 + I/I_{sat} + \delta^2/(\Gamma/2)^2)^2}(2\pi\Gamma)h\delta\sum_{j=1}^{M}(k_j \cdot v)(k_j \cdot e_j)e_j \tag{8}$$

$$\sum_{j=1}^{M}(F_j)_{\parallel v} \simeq \frac{1}{2}\frac{2I/I_{sat}}{(\Gamma/2)^2(1 + I/I_{sat} + \delta^2/(\Gamma/2)^2)^2}(2\pi\Gamma)h\delta\sum_{j=1}^{M}(k_j \cdot e_v)^2|v|e_v \tag{9}$$

As an example, when M=4N (where N represents a predetermined integer satisfying 1≤N), the wave vectors k_{4n-3}, k_{4n-2}, k_{4n-1} and k_{4n} are defined by Formulas (10), (11), (12) and (13) respectively, where ne {1, . . . , N}, and $e_{n,1}$ and $e_{n,2}$ are arbitrary unit direction vectors in directions each perpendicular to the unit direction vector e_v. Here, α_n, β_n, γ_n are constants which each depend on n and are greater than zero (that is, $\alpha_n>0$, $\beta_n>0$, $\gamma_n>0$). The condition (1) is satisfied by $\beta_n\neq0$ and $\gamma_n\neq0$.

[Formula 6]

$$k_{4n-3} = \frac{\alpha_n e_v - \beta_n e_{n,1}}{2} \tag{10}$$

$$k_{4n-2} = \frac{\alpha_n e_v - \beta_n e_{n,1}}{2} \tag{11}$$

$$k_{4n-1} = \frac{-\alpha_n e_v + \gamma_n e_{n,2}}{2} \tag{12}$$

$$k_{4n} = \frac{-\alpha_n e_v - \gamma_n e_{n,2}}{2} \tag{13}$$

For the wave vectors k_{4n-3}, k_{4n-2}, k_{4n-1} and k_{4n} defined by Formulas (10), (11), (12) and (13) respectively, Formulas

(14), (15) and (16) hold. Therefore, Formulas (7) and (2) hold, that is, the condition (a) is satisfied.

[Formula 7]

$$\sum_{j=1}^{M} k_j = \sum_{n=1}^{N} (k_{4a-3} + k_{4a-2} + k_{4n-1} + k_{4n}) = 0 \tag{14}$$

$$\sum_{j=1}^{M} (k_j \cdot v)(k_j \cdot e_j)e_j = \sum_{n=1}^{N} \{(k_{4n-3} \cdot v)(k_{4n-3} \cdot e_{n,1})e_{n,1} + (k_{4n-2} \cdot v)(k_{4n-2} \cdot e_{n,1})e_{n,1} + (k_{4n-1} \cdot v)(k_{4n-1} \cdot e_{n,2})e_{n,2} + (k_{4n} \cdot v)(k_{4n} \cdot e_{n,2})e_{n,2}\} = 0 \tag{15}$$

$$\sum_{j=1}^{M} (k_j \cdot e_v)^2 |v| e_v = \sum_{n=1}^{N} \alpha_n^2 |v| e_v \tag{16}$$

By replacing, by $(|v|-v_d)e_v$, v on the right side of Formula (9) in consideration of $\alpha_n \neq 0$ and Formula (16) with attention to Formula (3) under the condition of $\delta<0$, the left side of Formula (6) can be written as Formula (17).

[Formula 8]

$$\sum_{j=1}^{M} F_j = \sum_{n=1}^{N} \left\{ \frac{1}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + (\delta - k_{4n-3} \cdot (|v| - v_d)e_v)^2/(\Gamma/2)^2} (2\pi\Gamma)hk_{4n-3} + \frac{1}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + (\delta - k_{4n-2} \cdot (|v| - v_d)e_v)^2/(\Gamma/2)^2} (2\pi\Gamma)hk_{4n-2} + \frac{1}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + (\delta - k_{4n-1} \cdot (|v| - v_d)e_v)^2/(\Gamma/2)^2} (2\pi\Gamma)hk_{4n-1} + \frac{1}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + (\delta - k_{4n} \cdot (|v| - v_d)e_v)^2/(\Gamma/2)^2} (2\pi\Gamma)hk_{4n} \right\} \tag{17}$$

Therefore, a configuration satisfying the condition (b) is obtained by setting frequencies f_{4n-3}, f_{4n-2}, f_{4n-1} and f_{4n} to satisfy Formulas (18), (19), (20), and (21) respectively, where the frequency f_j represents the frequency of the laser beam **511** of the wave vector k_j. Here, the intensities of the laser beams **511** are equal to each other, and $\delta<0$. The wave vectors k_{4n-3}, k_{4n-2}, k_{4n-1} and k_{4n} in Formulas (18), (19), (20), and (21) satisfy Formulas (10), (11), (12), and (13), respectively.

[Formula 9]

$$f_{4n-3}=f_0+\delta+v_d k_{4n-3} \cdot e_v \tag{18}$$

$$f_{4n-2}=f_0+\delta+v_d k_{4n-2} \cdot e_v \tag{19}$$

$$f_{4n-1}=f_0+\delta+v_d k_{4n-1} \cdot e_v \tag{20}$$

$$f_{4n}=f_0+\delta+v_d k_{4n} \cdot e_v \tag{18}$$

When the angle between the course **505** of the cold atomic beam **131**, which is the moving direction e_v of the atoms, and the wave vector k_j is represented by θ_j, $|\theta_j| \neq \pi/2$ and $|\theta_j| \neq 0$ from $\alpha_n+\eta_n \neq 0$, $\alpha_n-\eta_n \neq 0$, $\beta_n \neq 0$, and $\gamma_n \neq 0$. Here, the sign of the angle is positive for counterclockwise rotation, and negative for clockwise rotation. Considering the contribution of the radiation pressure of the j-th laser beam **511** to the adjustment of the speeds of atoms, it is preferable that θ_j satisfies $\cos(\pi/4) \leq |\cos \theta_j| < 1$. Further, considering easiness of mounting, it is preferable that θ_j satisfies $\cos(\pi/4) \leq |\cos \theta_j| \leq \cos(\pi/10)$. In the above configuration example, $\theta_{4n-3}=-\theta_{4n-2}$ and $\theta_{4n-1}=-\theta_{4n}$.

The dispersion relation of the laser beam in vacuum is represented by $|k_j|=f_j/c$. Therefore, the frequencies f_{4n-3}, f_{4n-2}, f_{4n-1} and f_{4n} may be determined by Formulas (22), (23), (24) and (25) respectively.

[Formula 10]

$$f_{4n-3} = \frac{f_0 + \delta}{1 - \frac{v_d}{c}\cos\theta_{4n-3}} \tag{22}$$

$$f_{4n-2} = \frac{f_0 + \delta}{1 - \frac{v_d}{c}\cos\theta_{4n-2}} \tag{23}$$

$$f_{4n-1} = \frac{f_0 + \delta}{1 - \frac{v_d}{c}\cos\theta_{4n-1}} \tag{24}$$

$$f_{4n} = \frac{f_0 + \delta}{1 - \frac{v_d}{c}\cos\theta_{4n}} \tag{25}$$

From the physical consideration of Formula (14), the four laser beams **511** (that is, (4n−3)-th laser beam, (4n−2)-th laser beam, (4n−1)-th laser beam, 4n-th laser beam) are mutually superposed in one predetermined spatial region S_n through which the cold atomic beam **131** passes. Therefore, according to this configuration example, the condition (2) is also satisfied for each n.

As a specific example, FIG. **2** shows a configuration example in the case of M=4. In particular, FIG. **3** shows a configuration example in the case of $e_{n,1}=e_{n,2}$. In particular, FIG. **4** shows a configuration example in the case of $\beta_n=\gamma_n$. In particular, FIG. **5** shows a configuration example in the case of $e_{n,1}=e_{n,2}$ and $\beta_n=\gamma_n$. When a configuration example in the case of $e_{n,1}=e_{n,2}$ and $\beta_n=\gamma_n$ is defined as a unit, FIG. **6** and FIG. **7** show configuration examples including two or more units.

Another example will be described. The wave vectors k_{3n-2}, k_{3n-1}, and k_{3n} are defined by Formulas (26), (27) and (28) respectively, where M=3N (where N represents a predetermined integer satisfying 1≤N), $n \in \{1, \ldots, N\}$, and e_n is an arbitrary unit direction vector in a direction perpendicular to the unit direction vector e_v. Here, α_n and β_n are constants which each depend on n and are greater than zero (that is, $\alpha_n>0$, $\beta_n>0$). The condition (1) is satisfied by $\beta_n \neq 0$.

[Formula 11]

$$k_{3n-2}=-2\beta_n e_n \tag{26}$$

$$k_{3n-1}=\alpha_n e_v+\beta_n e_n \tag{27}$$

$$k_{3n}=-\alpha_n e_v+\beta_n e_n \tag{28}$$

For wave vectors k_{3n-2}, k_{3n-1}, and k_{3n} defined by Formulas (26), (27) and (28) respectively, Formulas (7) and (2) hold as in the case of M=4N. In other words, the condition (a) is satisfied.

Furthermore, with attention to Formula (3) under the condition of $\delta<0$ as in the case of M=4N, the left side of Formula (6) can be written as Formula (29).

[Formula 12]

$$\sum_{j=1}^{M} F_j = \sum_{n=1}^{N} \left\{ \frac{1}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + (\delta - k_{3n-2} \cdot (|v| - v_d) e_v)^2 / (\Gamma/2)^2} (2\pi\Gamma) h k_{3n-2} + \frac{1}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + (\delta - k_{3n-1} \cdot (|v| - v_d) e_v)^2 / (\Gamma/2)^2} (2\pi\Gamma) h k_{3n-1} + \frac{1}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + (\delta - k_{3n} \cdot (|v| - v_d) e_v)^2 / (\Gamma/2)^2} (2\pi\Gamma) h k_{3n} \right\} \quad (29)$$

Therefore, a configuration satisfying the condition (b) is obtained by setting frequencies f_{3n-2}, f_{3n-1}, and f_{3n} to satisfy Formulas (30), (31), and (32) respectively, where the frequency f_j represents the frequency of the laser beam **511** of the wave vector k_j. Here, the intensities of the laser beams **511** are equal to one another, and $\delta<0$. The wave vectors k_{3n-2}, k_{3n-1}, and k_{3n} of Formulas (30), (31) and (32) satisfy Formulas (26), (27) and (28), respectively.

[Formula 13]

$$f_{3n-2}=f_0+\delta \quad (30)$$

$$f_{3n-1}=f_0+\delta+v_d k_{3n-1}\cdot e_v \quad (31)$$

$$f_{3n}=f_0+\delta+v_d k_{3n}\cdot e_v \quad (32)$$

When the angle between the course **505** of the cold atomic beam **131**, which is the moving direction e_v of the atoms, and the wave vector k_j is represented by θ_j, $\theta_{3n-2}=\pi/2$, $0<-\theta_{3n-1}<\pi/2$, and $\theta_{3n}=\pi-\theta_{3n-1}$ hold from $\alpha_n>0$, and $\beta_n>0$. Considering the contribution of the radiation pressure of the j-th laser beam **511** to the adjustment of the speeds of atoms, it is preferable that θ_{3n-1} satisfies $\cos(\pi/4)\le\cos\theta_{3n-1}<1$, and in consideration of easiness of mounting, it is further preferable that θ_{3n-1} satisfies $\cos(\pi/4)\le\cos\theta_{3n-1}\le\cos(\pi/10)$.

The dispersion relation of the laser beam in vacuum is represented by $|k_j|=f_j/c$. Therefore, the frequencies f_{3n-1} and f_{3n} may be determined according to Formulas (33) and (34) respectively.

[Formula 14]

$$f_{3n-1} = \frac{f_0+\delta}{1-\frac{v_d}{c}\cos\theta_{3n-1}} \quad (33)$$

$$f_{3n} = \frac{f_0+\delta}{1+\frac{v_d}{c}\cos\theta_{3n-1}} \quad (34)$$

As in the case of M=4N, the three laser beams **511** (that is, (3n−2)-th laser beam, (3n−1)-th laser beam, and 3n-th laser beam) are mutually superposed in one predetermined special region S_n through which the cold atomic beam **131** passes, so that the condition (2) is also satisfied for each n in this configuration example.

As a specific example, a configuration example in the case of M=3 is shown in FIG. **8**. When the configuration example of FIG. **8** is set as one unit, configuration examples including two or more units are shown in FIGS. **9** and **10**.

In each of the configurations shown in FIGS. **3**, **5** and **7**, the spatial region S_n may be subjected to laser cooling in a direction that is perpendicular to the unit direction vector e_v and perpendicular to the unit direction vector $e_{n,1}$ ($e_{n,2}$). In each of the configurations of FIGS. **8** and **10**, the spatial region S_n (S_m) may be subjected to laser cooling in a direction that is perpendicular to the unit direction vector e_v and perpendicular to the unit direction vector e_n.

For example, with respect to a rubidium atom, the resonance frequency f_0 of the D_2 line ($5S_{1/2}\rightarrow 5P_{3/2}$ transition) is 384.23 THz and the natural width Γ of the transition is about 6 MHz, so that the adjuster **500** can adopt a configuration satisfying the above conditions (1), (2), (a) and (b) when $\delta=-\Gamma/2$, $v_d=20$[m/s] in the case that the mode of the atomic speed distribution in the traveling direction of the cold atomic beam **131** from the atomic beam deflector **140** is 20 m/s, $\theta_{4n-3}=\pi/4$, $\theta_{4n-2}=-\pi/4$, and $\theta_{4n-1}=3\pi/4$, $\theta_{4n}=-3\pi/4$, and M=4.

As is clear from the present embodiment, the feature of the adjuster **500** is not in a hardware configuration of the laser beam generator **501**, but is rather recognized as various conditions that the M laser beams **511** have to satisfy. In addition, existing laser beam generation techniques can be adopted as a technique for generating the laser beam **511**. Thus, detailed description of the hardware configuration of the laser beam generator **501** is omitted. When the laser beam generator **501** generates a moving standing light wave as in the case of the configuration example described above, in imitation of the optical configuration of the moving standing light wave generator **300** described later, the hardware configuration of the laser beam generator **501** is implemented, for example, by a combination of a laser light source, an optical fiber, an AOM (acousto-optic modulator), a beam shaper, and the like.

Individual atoms contained in cold atomic beam **131** from the adjuster **500** are set to be at the same energy level by optical pumping as needed. A cold atomic beam **131** containing atoms at the same energy level enters the interference unit **200**.

In the interference unit **200**, the cold atomic beam **131** passes through three moving standing light waves **200***a*, **200***b*, and **200***c*. A first moving standing light wave **200***a* and a third moving standing light wave **200***c* out of the three moving standing light waves **200***a*, **200***b*, and **200***c* have a property called π/2 pulse described later, and the second moving standing light wave **200***b* has a property called π pulse described later. Each moving standing light wave is generated by two counter-propagating laser beams having different frequencies. The moving standing light wave drifts at a speed which is much smaller than the speed c of light. However, the difference between the wave number of one laser beam and the wave number of the other laser beam is sufficiently small.

Here, an example of an optical configuration (see FIG. **11**) of the moving standing light wave generator **300** for generating the three moving standing light waves **200***a*, **200***b*, and **200***c* will be described.

The moving standing light wave generator **300** includes three optical modulation devices **320***a*, **320***b* and **320***c* corresponding to the three moving standing light waves **200***a*, **200***b* and **200***c*. The optical modulation device **320***x* ($x\in\{a, b, c\}$) includes optical fibers **321***x* and **324***x* through which a laser beam propagates, and a frequency shifter **323***x* that is connected to the optical fibers **321***x* and **324***x* and shifts the frequency of the laser beam. The frequency shifter **323***x* is, but is not limited to, is an AOM or an EOM (electro-optic modulator), for example.

A laser beam L from a laser light source **311** passes through EOM **312** to be shifted in frequency by a predetermined frequency. The frequency-shifted laser beam L is equally divided by an optical fiber coupler **313***a*. One of the two laser beams L coming out of the optical fiber coupler **313***a* is equally divided by an optical fiber coupler **313***c*, and the other of the two laser beams L coming out of the optical fiber coupler **313***a* is equally divided by an optical fiber coupler **313***b*. One of the two laser beams L coming out of the optical fiber coupler **313***b* is equally divided by an optical fiber coupler **313***d*, and the other of the two laser beams L coming out of the optical fiber coupler **313***b* is equally divided by an optical fiber coupler **313***e*.

One of the two laser beams L coming out of the optical fiber coupler **313***c* is attenuated by a VOA (Variable Optical Attenuator) **314***a*, and then subjected to shaping so as to be a desired beam (for example, a Gaussian beam) by a beam shaper **315***a* including, for example, a lens, a collimator, and so on. The thus-obtained beam $L_{a,1}$ enters the interference unit **200**. The other of the two laser beams L coming out of the optical fiber coupler **313***c* is guided to an AOM **323***a* without crossing the atomic beam by an optical fiber **321***a* with one end thereof connected to the optical fiber coupler **313***c* by an unillustrated optical connector. An intermediate part of the optical fiber **321***a* is not depicted in FIG. **11** to make the drawing easily visible.

One of the two laser beams L coming out of the optical fiber coupler **313***d* is attenuated by a VOA **314***b*, and then subjected to shaping so as to be a desired beam (for example, a Gaussian beam) by a beam shaper **315***b* including, for example, a lens, a collimator, and so on. The thus-obtained beam $L_{b,1}$ enters the interference unit **200**. The other of the two laser beams L coming out of the optical fiber coupler **313***d* is guided to an AOM **323***b* without crossing the atomic beam by an optical fiber **321***b* with one end thereof connected to the optical fiber coupler **313***d* by an unillustrated optical connector. An intermediate part of the optical fiber **321***b* is not depicted in FIG. **11** to make the drawing easily visible.

One of the two laser beams L coming out of the optical fiber coupler **313***e* is attenuated by a VOA **314***c*, and then subjected to shaping so as to be a desired beam (for example, a Gaussian beam) by a beam shaper **315***c* including, for example, a lens, a collimator, and so on. The thus-obtained beam $L_{c,1}$ enters the interference unit **200**. The other of the two laser beams L coming out of the optical fiber coupler **313***e* is guided to an AOM **323***c* without crossing the atomic beam by an optical fiber **321***c* with one end thereof connected to the optical fiber coupler **313***e* by an unillustrated optical connector. An intermediate part of the optical fiber **321***c* is not depicted in FIG. **11** to make the drawing easily visible.

The other end of the optical fiber **321***x* ($x \in \{a, b, c\}$) is connected to the frequency shifter **323***x* by an optical connector, and thus the laser beam L enters the frequency shifter **323***x*. The frequency of laser beam L is shifted by the frequency shifter **323***x*. The amount of shift depends on the frequency f_x of a signal input to the frequency shifter **323***x*. As a result, the laser beam L is phase-modulated. One end of the optical fiber **324***x* is connected to the frequency shifter **323***x* by an optical connector, and thus the laser beam L coming out of the frequency shifter **323***x* enters the optical fiber **324***x*. The laser beam L comes out of an optical connector attached to the other end of the optical fiber **324***x*, and is subjected to shaping so as to be a desired beam (for example, a Gaussian beam) by a beam shaper **316***x* including, for example, a lens, a collimator, and so on. The thus-obtained beam $L_{x,2}$ enters interference unit **200**.

As a result, the laser beam $L_{x,1}$ that has not passed through the optical modulation device **320***x* and the laser beam $L_{x,2}$ that has passed through the optical modulation device **320***x* counter-propagate in a free space to generate a moving standing light wave **200***x* ($x \in \{a, b, c\}$).

The atomic interference system in the interference unit **200** uses transition between two levels of an atom caused by light irradiation. Therefore, from the viewpoint of avoiding decoherence caused by spontaneous emission, long-lived transition between two levels is generally used. For example, when the atomic beam is an alkali-metal atomic beam, the atomic interference system uses induced Raman transition between two levels included in a hyperfine structure in a ground state. Let $|g\rangle$ be the lowest energy level and $|e\rangle$ be an energy level higher than $|g\rangle$, in the hyperfine structure. In general, the induced Raman transition between two levels is achieved by a moving standing light wave that is formed by counter irradiation of two laser beams, whose difference frequency is nearly equal to the resonance frequency of $|g\rangle$ and $|e\rangle$.

The atomic interference using a two-photon Raman process caused by the moving standing light waves will be described below.

In the course of the cold atomic beam **131** passing through the first moving standing light wave **200***a*, the state of every atom changes from an initial state $|g, p\rangle$ to a superposition state of $|g, p\rangle$ and $|e, p+h(k_1-k_2)\rangle$. Note that p represents momentum of an atom, k_1 represents a wave number of one of the two laser beams that form the moving standing light wave, and k_2 represents a wave number of the other laser beam ($p_0=p$, $p_1=p+h(k_1-k_2)$ in FIG. **1**). For example, by appropriately setting a time Δt required to pass through the first moving standing light wave **200***a* (that is, a time of interaction between an atom and the moving standing light wave), the ratio between the existence probability of $|g, p\rangle$ and the existence probability of $|e, p+h(k_1-k_2)\rangle$ immediately after the passage through the first moving standing light wave **200***a* is 1:1. An atom acquires momentum of two photons while transiting from $|g, p\rangle$ to $|e, p+h(k_1-k_2)\rangle$ through absorption and emission of the two photons traveling against each other. Therefore, the moving direction of atoms in the state $|e, p+h(k_1-k_2)\rangle$ deviates from the moving direction of atoms in the state $|g, p\rangle$. In other words, in the course of the cold atomic beam **131** passing through the first moving standing light wave **200***a*, the cold atomic beam **131** splits into, at a ratio of 1:1, an atomic beam composed of atoms in the state $|g, p\rangle$ and an atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$. The first moving standing light wave **200***a* is called $\pi/2$ pulse and has a function as a splitter for the atomic beam.

After the split, the atomic beam composed of atoms in the state $|g, p\rangle$ and the atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$ pass through the second moving standing light wave **200***b*. For example, by setting a time required to pass through the second moving standing light wave **200***b* at $2\Delta t$, in other words, by setting a time of interaction between an atom and the moving standing light wave at $2\Delta t$, the atomic beam composed of atoms in the state $|g, p\rangle$ is reversed to an atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$ in the course of passing through the second moving standing light wave **200***b*, and the atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$ is reversed to an atomic beam composed of atoms in the state $|g, p\rangle$ in the course of passing through the second moving standing light wave **200***b*. At this time, as for the former, the moving direction of the atoms that have transited from $|g, p\rangle$ to $|e, p+h(k_1-k_2)\rangle$ deviates from the moving direction of the atoms in the state $|g, p\rangle$, as described above. As a result, the traveling direction of the atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$ after the passage through the second moving standing light wave **200***b* becomes parallel to the traveling direction of the atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$ after the passage through the first moving standing light wave **200***a*. Moreover, as for the latter, an atom loses the same momentum as the momentum gained from two photons in transition from $|e, p+h(k_1-k_2)\rangle$ to $|g, p\rangle$ through absorption and emission of the two photons traveling against each other. That is, the moving direction of atoms after transition from $|e, p+h(k_1-k_2)\rangle$ to $|g, p\rangle$ deviates from the moving direction of atoms in the state $|e, p+h(k_1-k_2)\rangle$ before the transition. As a result, the traveling direction of the atomic beam composed of atoms in the state $|g, p\rangle$ after the passage through the second moving standing light wave **200***b* becomes parallel to the traveling direction of the atomic beam composed of atoms in the state $|g, p\rangle$ after the passage through the first moving standing light wave **200***a*. The second moving standing light wave **200***b* is called n pulse, and has a function as a mirror for the atomic beams.

After the reversal, the atomic beam composed of atoms in the state $|g, p\rangle$ and the atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$ pass through the third moving standing light wave **200***c*. Assume that the cold atomic beam **131** passes through the first moving standing light wave **200***a* at time $t_1=T$ and the two atomic beams after the split pass through the second moving standing light wave **200***b* at time $t_2=T+\Delta T$. Then, two atomic beams after the reversal pass through the third moving standing light wave **200***c* at time $t_3=T+2\Delta T$. At the time t_3, the atomic beam composed of atoms in the state $|g, p\rangle$ after the reversal and the atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$ after the reversal cross each other. For example, by appropriately setting a time required to pass through the third moving standing light wave **200***c*, that is, a time of interaction between an atom and the moving standing light wave, specifically, by setting a time required to pass through the third moving standing light wave **200***c* at Δt mentioned above, it is possible to obtain a cold atomic beam **131***b* corresponding to a superposition state of $|g, p\rangle$ and $|e, p+h(k_1-k_2)\rangle$ of individual atoms contained in a region of intersection between the atomic beam composed of atoms in the state $|g, p\rangle$ and the atomic beam composed of atoms in the state $|e, p+h(k_1-k_2)\rangle$. This cold atomic beam **131***b* is an output of the interference unit **200**. The third moving standing light wave **200***c* is called $\pi/2$ pulse and has a function as a combiner for the atomic beams.

The monitor **400** irradiates the cold atomic beam **131***b* from the interference unit **200** with probe light **408**, and detects fluorescence from the atoms in the state $|e, p+h(k_1-k_2)\rangle$ using a photodetector **409**. Examples of the photodetector **409** include a photomultiplier tube and a fluorescence photodetector. Alternatively, in the case of using a channeltron as the photodetector **409**, the atomic beam of one of the two paths after the passage through the third moving standing light wave **200***c* may be ionized by a laser beam or the like in place of the probe light, and ions may be detected with the channeltron.

In the case that the Mach-Zehnder atomic interferometer **800** is applied to an atomic gyroscope that is the inertial sensor **900**, the monitor **400** may perform processing for detecting an angular velocity or an acceleration as a physical quantity from the population of atoms in an excited state. While an angular velocity or an acceleration in a plane containing two paths of the atomic beams from the irradiation of the first moving standing light wave **200***a* to the irradiation of the third moving standing light wave **200***c* is applied to the Mach-Zehnder atomic interferometer **800**, a phase difference is produced in the two paths of the atomic beams from the irradiation of the first moving standing light wave **200***a* to the irradiation of the third moving standing light wave **200***c*. This phase difference is reflected in the existence probabilities of the state $|g\rangle$ and the state $|e\rangle$ of the individual atoms after the passage through the third moving standing light wave **200***c*. Therefore, the monitor **400** can detect the angular velocity or the acceleration by monitoring the cold atomic beam **131***b* from the interference unit **200**, that is, the atomic beam obtained after the passage through the third moving standing light wave **200***c*, that is, by measuring the population of atoms in the excited state $|e\rangle$, for example. The processing for detecting an angular velocity or an acceleration from the population of atoms in an excited state has been well known, and thus the description thereof is omitted.

Modifications

For example, the above-described embodiment utilizes Mach-Zehnder atomic interference in which one splitting, one reversal, and one mixing are performed using three moving standing light waves; the atomic interferometer of the present invention is not limited to such an embodiment, and it may be implemented as an embodiment, for example, using multistage Mach-Zehnder atomic interference in which more than one splitting, more than one reversal, and more than one mixing are performed. See Reference literature 2 for such multistage Mach-Zehnder atomic interference.

(Reference literature 2) Takatoshi Aoki et al., "High-finesse atomic multiple-beam interferometer comprised of copropagating stimulated Raman-pulse fields," Phys. Rev. A 63, 063611 (2001)—Published 16 May 2001.

Further, the atomic interferometer of the present invention is not limited to the Mach-Zehnder atomic interferometer, and it may be, for example, a Ramsey-Bordé atomic interferometer.

In the above-described embodiments, the cold atomic beam generator **130** has the configuration including the $2D^+$-MOT mechanism. However, the cold atomic beam generator **130** is not limited to the configuration including the $2D^+$-MOT mechanism because the cold atomic beam generator **130** may use a pushing laser beam to generate a cold atomic beam from atoms trapped in space. The cold atomic beam generator **130** may have, for example, a configuration including an LVIS mechanism (for example, Reference literature 3), a configuration including a 2D-MOT mechanism (for example, Reference literature 4), a configuration including a 2D-HP MOT mechanism (for example, Reference literature 5), or a configuration for generating a cold atomic beam by using a laser beam and a pyramidal perforated retroreflector (for example, Reference literature 6).

(Reference literature 3) Z. Lu, K. Corwin, M. Renn, M. Anderson, E. Cornell and C. Wieman: "Low-Velocity Intense Source of Atoms from a Magneto-optical Trap," Phys. Rev. Lett., 77, 16, pp. 3331-3334 (1996).

(Reference literature 4) J. Schoser, A. Batar, R. Low, V. Schweikhard, A. Grabowski, Yu. B. Ovchinnikov, and T. Pfau, "Intense source of cold Rb atoms from a pure two-dimensional magneto-optical trap," PHYSICAL REVIEW A, 66, 023410 2002.

(Reference literature 5) Jia-Qiang Huang, Xue-Shu Yan, Chen-Fei Wu, Jian-Wei Zhang, and Li-Jun Wang, "Intense source of cold cesium atoms based on a two-dimensional magneto-optical trap with independent axial cooling and pushing," Chin. Phys. B Vol. 25, No. 6 063701 (2016).

(Reference literature 6) J. Arlt, O. Marago, S. Webster, S. Hopkins and C. Foot: "A pyramidal magnetooptical trap as a source of slow atoms," Opt. Commun., December, pp. 303-309 (1998).

Further, in the above-described embodiments, the atomic beam deflector **140** has the configuration including the 2D-MOT mechanism. However, since the atomic beam deflector **140** is required only to deflect the cold atomic beam from the cold atomic beam generator **130**, the atomic beam deflector **140** is not limited to the configuration including the 2D-MOT mechanism, and the atomic beam deflector **140** may have a configuration including, for example, a moving molasses mechanism.

To give a simple example, the moving molasses mechanism includes at least one pair of laser beams. The one pair of laser beams forms a moving standing light wave. The moving standing light wave imparts speeds to atoms in its drift direction. In the case that the moving molasses mechanism includes two pairs of laser beams, each pair forms a moving standing light wave. Atoms entering an intersection region of the two moving standing light waves are given speeds in a composite direction of the drift directions of the two moving standing light waves.

In the case that the atomic beam deflector **140** has a configuration including the moving molasses mechanism, the cold atomic beam generator **130** and the atomic beam deflector **140** has such a positional relationship that the course of the moving standing light wave in the moving molasses mechanism intersects (preferably orthogonally) with the course of the cold atomic beam from the cold atomic beam generator.

The cold atomic beam **131** and the leaking pushing laser beam **121** enter the atomic beam deflector **140** having the configuration including the moving molasses mechanism. From the above-described positional relationship between the cold atomic beam generator **130** and the atomic beam deflector **140**, the cold atomic beam **131** and the leaking pushing laser beam **121** obliquely intersect with the course of the moving standing light wave in the moving molasses mechanism of the atomic beam deflector **140**. Then, the traveling direction of the cold atomic beam **131** is changed by the principle of moving molasses. However, since the pushing laser beam **121** is not affected by the moving molasses mechanism, the traveling direction of the pushing laser beam **121** is not changed. Therefore, the atomic beam deflector **140** causes the cold atomic beam **131** to travel in a direction different from the traveling direction of the pushing laser beam **121**.

Supplement

The above conditions (1), (2), (a), and (b) will be described supplementarily. For example, when the atomic interferometer **800** is produced or transferred, the laser beams **511** and the atomic beam **131** do not exist in the atomic interferometer **800** at that time. However, the courses **503** of the laser beams **511** can be specified, for example, by the orientation of the laser beam emission ports or the angles of the mirrors. Furthermore, the course **505** of the atomic beam **131** can be specified, for example, from the positional relationship among the cold atomic beam generation apparatus **100**, the adjuster **500**, and the interference unit **200**. In other words, even in a condition that the laser beams **511** and the atomic beam **131** do not exist, it is possible to determine whether each of the conditions (1) and (2) is satisfied. Furthermore, since the intensities, the frequencies and so on of the laser beams **511** that can be generated by the laser beam generator **501** can be specified from the hardware configuration of the laser beam generator **501**, it is possible to determine whether each of the conditions (a) and (b) is satisfied even in a condition that the laser beams **511** and the atomic beam **131** do not exist. Therefore, it is intended that the scopes of protection of the inertial sensor, the atomic interferometer, and the adjuster enumerated in Claims are not limited to those under conditions in which laser beams and an atomic beam exist, but also expand to those under conditions in which neither laser beams nor an atomic beam exist.

While the invention has been described with reference to the exemplary embodiments, it would be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular system, device or component thereof to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiments disclosed for carrying out the present invention, but that the invention will include all embodiments falling within the scope of the appended claims.

Moreover, the use of the terms "first," "second," etc., if any, does not denote any order or importance, but rather the terms "first," "second," etc. are used to distinguish one element from another. The terminology used in the present specification is for the purpose of describing particular embodiments only and is not intended to limit the invention in any way. The term "comprising" and its conjugations, when used in the present specification and/or the appended claims, specify the presence of stated features, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, steps, operations, elements, components, and/or groups thereof. The term "and/or", if any, includes any and all combinations of one or more of the associated listed elements. In the claims and the specification, unless otherwise noted, the terms "connect", "couple", "join", "link", or synonyms therefor and all the word forms thereof, if any, do not necessarily deny the presence of one or more intermediate elements between two elements, for instance, two elements "connected" or "coupled" to each other or "linked" to each other.

Unless otherwise defined, all terms (including technical terms and scientific terms) used in the present specification have the same meaning as commonly understood by those skilled in the art to which the invention belongs. Moreover, terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant arts and the present disclosure, and should not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

In describing the invention, it will be understood that a number of techniques and steps are disclosed. Each of these has individual benefit and each can also be used in conjunction with one or more, or in some cases all, of the other disclosed techniques. Accordingly, for the sake of clarity, this description will refrain from repeating every possible combination of the individual techniques or steps in an unnecessary fashion. Nevertheless, the present specification and claims should be read with the understanding that such combinations are entirely within the scope of the invention and the claims.

The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below, if any, are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed.

The foregoing description of the embodiments of the invention has been presented for the purpose of illustration and description. It is not intended to be exhaustive and to limit the invention to the precise form disclosed. Modifications or variations are possible in light of the above teaching. The embodiments were chosen and described to provide the best illustration of the principles of the invention and its practical application, and to enable one of ordinary skill in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. All such modifications and variations are within the scope of the invention as determined by the appended claims when interpreted in accordance with the breadth to which they are fairly, legally, and equitably entitled.

DESCRIPTION OF REFERENCE NUMERALS

100 Cold atomic beam generation apparatus
100*a* Partition
110 Atom source
121 Pushing laser beam
130 Cold atomic beam generator
140 Atomic beam deflector
131 Cold atomic beam
131*b* Cold atomic beam
200 Interference unit
200*a* First moving standing light wave
200*b* Second moving standing light wave
200*c* Third moving standing light wave
300 Moving standing light wave generator
400 Monitor
408 Probe light
409 Photodetector
500 Adjuster
501 Laser beam generator
503 Course
505 Course
511 Laser beam
800 Atomic interferometer
900 Inertial sensor
S_n Spatial region
S_m Spatial region

What is claimed is:

1. An inertial sensor comprising:
a cold atomic beam generation apparatus to continuously generate an atomic beam cooled;
an adjuster to make speeds of atoms contained in the atomic beam close to a predetermined speed;
a moving standing light wave generator to generate three or more moving standing light waves;
an interference unit to obtain an atomic beam resulting from interaction between the atomic beam from the adjuster and the three or more moving standing light waves; and
a monitor to detect a physical quantity by observation of the atomic beam from the interference unit,
wherein the adjuster comprises a laser beam generator to generate M laser beams satisfying the following conditions A), B) and C), where M is a predetermined integer satisfying 3≤M:
A) a course of each of the M laser beams intersects with a course of the atomic beam passing through the adjuster;
B) a component, in a direction perpendicular to the course of the atomic beam passing through the adjuster, of a sum of radiation pressure vectors that the M laser beams respectively have is zero; and
C) a component, in a direction of the course of the atomic beam passing through the adjuster, of the sum of the radiation pressure vectors that the M laser beams respectively have is negative for the atoms having speeds greater than the predetermined speed, and positive for the atoms having speeds smaller than the predetermined speed.

2. An atomic interferometer comprising:
a cold atomic beam generation apparatus to continuously generate an atomic beam cooled;
an adjuster to make speeds of atoms contained in the atomic beam close to a predetermined speed;
a moving standing light wave generator to generate three or more moving standing light waves; and
an interference unit to obtain an atomic beam resulting from interaction between the atomic beam from the adjuster and the three or more moving standing light waves,
wherein the adjuster comprises a laser beam generator to generate M laser beams satisfying the following conditions A), B) and C), where M is a predetermined integer satisfying 3≤M:
A) a course of each of the M laser beams intersects with a course of the atomic beam passing through the adjuster;
B) a component, in a direction perpendicular to the course of the atomic beam passing through the adjuster, of a sum of radiation pressure vectors that the M laser beams respectively have is zero; and
C) a component, in a direction of the course of the atomic beam passing through the adjuster, of the sum of the radiation pressure vectors that the M laser beams respectively have is negative for the atoms having speeds greater than the predetermined speed, and positive for the atoms having speeds smaller than the predetermined speed.

3. The atomic interferometer according to claim **2**, wherein the cold atomic beam generation apparatus comprises:
an atom source;
a cold atomic beam generator to generate, by using a pushing laser beam, the atomic beam from atoms trapped in space, the atoms being from the atom source; and
an atomic beam deflector that the atomic beam from the cold atomic beam generator enters,
the atomic beam deflector comprises a two-dimensional magneto-optical trapping mechanism or a moving molasses mechanism,
a course of the atomic beam from the cold atomic beam generator matches a course of the pushing laser beam,
in a case that the atomic beam deflector comprises the two-dimensional magneto-optical trapping mechanism, a zero magnetic field line of a quadrupole magnetic field in the two-dimensional magneto-optical trapping

mechanism intersects with the course of the atomic beam from the cold atomic beam generator, and

in a case that the atomic beam deflector comprises the moving molasses mechanism, a course of a moving standing light wave in the moving molasses mechanism intersects with the course of the atomic beam from the cold atomic beam generator.

4. A method of making speeds of atoms contained in an atomic beam close to a predetermined speed, the method comprising simultaneously irradiating the atomic beam with M laser beams satisfying the following conditions A), B) and C), where M is a predetermined integer satisfying $3 \leq M$:

A) a course of each of the M laser beams intersects with a course of the atomic beam;

B) a component, in a direction perpendicular to the course of the atomic beam, of a sum of radiation pressure vectors that the M laser beams respectively have is zero; and

C) a component, in a direction of the course of the atomic beam, of the sum of the radiation pressure vectors that the M laser beams respectively have is negative for the atoms having speeds greater than the predetermined speed, and positive for the atoms having speeds smaller than the predetermined speed.

5. The method according to claim **4**, wherein the atomic beam is a cold atomic beam, the cold atomic beam being composed of atoms whose speeds in a direction perpendicular to a course of the cold atomic beam are suppressed.

6. An apparatus for making speeds of atoms contained in an atomic beam close to a predetermined speed, the apparatus comprising a laser beam generator to generate M laser beams satisfying the following conditions A), B) and C), where M is a predetermined integer satisfying $3 \leq M$:

A) a course of each of the M laser beams intersects with a course of the atomic beam;

B) a component, in a direction perpendicular to the course of the atomic beam, of a sum of radiation pressure vectors that the M laser beams respectively have is zero; and

C) a component, in a direction of the course of the atomic beam, of the sum of the radiation pressure vectors that the M laser beams respectively have is negative for the atoms having speeds greater than the predetermined speed, and positive for the atoms having speeds smaller than the predetermined speed.

7. The apparatus according to claim **6**, wherein

$M=4N$, where N is a predetermined integer satisfying $1 \leq N$,

intensities of the M laser beams are equal to one another, wave vectors k_{4n-3}, k_{4n-2}, k_{4n-1} and k_{4n} are respectively expressed by

$$k_{4n-3} = \frac{\alpha_n e_v + \beta_n e_{n,1}}{2}$$

$$k_{4n-2} = \frac{\alpha_n e_v - \beta_n e_{n,1}}{2}$$

$$k_{4n-1} = \frac{-\alpha_n e_v + \gamma_n e_{n,2}}{2}$$

$$k_{4n} = \frac{-\alpha_n e_v - \gamma_n e_{n,2}}{2},$$

where e_v is a unit direction vector in the direction of the course of the atomic beam, $e_{n,1}$ and $e_{n,2}$ are arbitrary unit direction vectors in directions each perpendicular to the unit direction vector e_v, $n \in \{1, \ldots, N\}$, $\alpha_n > 0$, $\beta_n > 0$, and $\gamma_n > 0$, and

frequencies f_{4n-3}, f_{4n-2}, f_{4n-1} and f_{4n} are respectively expressed by

$$f_{4n-3} = f_0 + \delta + v_d k_{4n-3} \cdot e_v$$

$$f_{4n-2} = f_0 + \delta + v_d k_{4n-2} \cdot e_v$$

$$f_{4n-1} = f_0 + \delta + v_d k_{4n-1} \cdot e_v$$

$$f_{4n} = f_0 + \delta + v_d k_{4n} \cdot e_v,$$

where v_d is the predetermined speed, f_{4n-3} is a frequency of a laser beam of the wave vector k_{4n-3}, f_{4n-2} is a frequency of a laser beam of the wave vector k_{4n-2}, f_{4n-1} is a frequency of a laser beam of the wave vector k_{4n-1}, f_{4n} is a frequency of a laser beam of the wave vector k_{4n}, and $\delta < 0$.

8. The apparatus according to claim **7**, wherein $\cos(\pi/4) \leq |\cos\theta_{4n-3}| < 1$ and $\cos(\pi/4) \leq |\cos\theta_{4n-1}| < 1$, where θ_{4n-3} is an angle between the unit direction vector e_v and the wave vector k_{4n-3}, and θ_{4n-1} is an angle between the unit direction vector e_v and the wave vector k_{4n-1}.

9. The apparatus according to claim **6**, wherein

$M=3N$, where N is a predetermined integer satisfying $1 \leq N$,

intensities of the M laser beams are equal to one another, wave vectors k_{3n-2}, k_{3n-1} and k_{3n} are respectively expressed by

$$k_{3n-2} = -2\beta_n e_n$$

$$k_{3n-1} = \alpha_n e_v + \beta_n e_n$$

$$k_{3n} = -\alpha_n e_v + \beta_n e_n,$$

where e_v is a unit direction vector in the direction of the course of the atomic beam, e_n is an arbitrary unit direction vector in a direction perpendicular to the unit direction vector e_v, $n \in \{1, \ldots, N\}$, $\alpha_n > 0$, and $\beta_n > 0$, and

frequencies f_{3n-2}, f_{3n-1}, and f_{3n} are respectively expressed by

$$f_{3n-2} = f_0 + \delta$$

$$f_{3n-1} = f_0 + \delta + v_d k_{3n-1} \cdot e_{v)}$$

$$f_{3n} = f_0 + \delta + v_d k_{3n} \cdot e_v,$$

where v_d is the predetermined speed, f_{3n-2} is a frequency of a laser beam of the wave vector k_{3n-2}, f_{3n-1} is a frequency of a laser beam of the wave vector k_{3n-1}, f_{3n} is a frequency of a laser beam of the wave vector k_{3n}, and $\delta < 0$.

10. The apparatus according to claim **9**, wherein $\cos(\pi/4) \leq |\cos\theta_{3n-1}| < 1$, where θ_{3n-1} is an angle between the unit direction vector e_v and the wavenumber vector k_{3n-1}.

11. The apparatus according to claim **6**, wherein the atomic beam is a cold atomic beam, the cold atomic beam being composed of atoms whose speeds in a direction perpendicular to a course of the cold atomic beam are suppressed.

12. The apparatus according to claim **7**, wherein the atomic beam is a cold atomic beam, the cold atomic beam being composed of atoms whose speeds in a direction perpendicular to a course of the cold atomic beam are suppressed.

13. The apparatus according to claim **8**, wherein the atomic beam is a cold atomic beam, the cold atomic beam being composed of atoms whose speeds in a direction perpendicular to a course of the cold atomic beam are suppressed.

14. The apparatus according to claim **9**, wherein the atomic beam is a cold atomic beam, the cold atomic beam being composed of atoms whose speeds in a direction perpendicular to a course of the cold atomic beam are suppressed.

15. The apparatus according to claim **10**, wherein the atomic beam is a cold atomic beam, the cold atomic beam being composed of atoms whose speeds in a direction perpendicular to a course of the cold atomic beam are suppressed.

16. The apparatus according to claim **6**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

17. The apparatus according to claim **7**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

18. The apparatus according to claim **8**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

19. The apparatus according to claim **9**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

20. The apparatus according to claim **10**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

21. The apparatus according to claim **11**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

22. The apparatus according to claim **12**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

23. The apparatus according to claim **13**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

24. The apparatus according to claim **14**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

25. The apparatus according to claim **15**, wherein the M laser beams are mutually superposed in one predetermined spatial region through which the atomic beam passes.

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