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(54) Title: ATOMIC MAGNETOMETER AND MAGNETIC SENSING METHOD
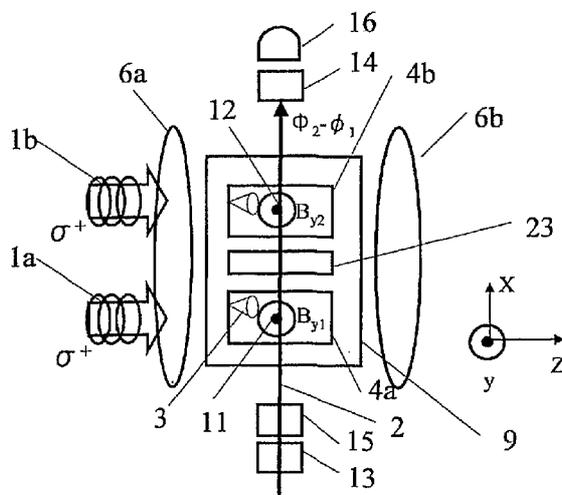
Fig. 2

(57) Abstract: An atomic magnetometer includes a light source for a probe beam and a medium in which the probe beam is to be propagated. The medium (3) is a substance which sequentially changes a polarization rotation angle of the probe beam depending on a magnetic field intensity at a first measurement position (11) and a magnetic field intensity at a subsequent second measurement position (12) different from the first measurement position. The atomic magnetometer directly measures a difference between the magnetic field intensity at the first measurement position and the magnetic field intensity at the second measurement position as the difference in polarization rotation angle, along a propagation path of the probe beam which results of performing optical subtraction.

DESCRIPTION

ATOMIC MAGNETOMETER AND MAGNETIC SENSING METHOD

5   [TECHNICAL FIELD]

The present invention relates to a

magnetometer for measuring a magnetic field intensity.

Particularly, the present invention relates to an

atomic magnetometer using alkali metal gas or rare gas

10   and a magnetic sensing method.

[BACKGROUND ART]

A high-sensitivity atomic magnetometer using

spin of alkali metal gas or rare gas has been proposed.

15   U.S. Patent No. 7,038,450 has proposed an atomic

magnetometer in which a cell including an alkali metal

vapor is irradiated with linearly polarized light

(beam) from a linearly polarized light source for a

pump beam and with circularly polarized light (beam)

20   from a circularly polarized light source for a probe

beam. Further, in order to measure a polarization

rotation angle of the probe beam, a photo-diode array

is used as a photo-detector.

Incidentally, information on a magnetic field

25   intensity (strength) depending on a measurement

position is measured as magnetic field gradient

information in some cases. In such cases, differential

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information of the magnetic field intensity (magnetic
field gradient information) is obtained by using
differential information on electric signals obtained
by being detected through a photo-detector provided
5   correspondingly to each of measurement positions.

However, actually, it is considered that a
condition concerning an amplification factor or noise
of an individual photo-detector per se is not strictly
uniformized. That is, when the magnetic field gradient
10   information is intended to be obtained by using the
electric signals obtained from the photo-detector,
there is liability to mixing of noise, on the basis of
characteristic difference between individual
photo-detectors, in the magnetic field gradient
15   information.

[DISCLOSURE OF THE INVENTION]

In view of the above-described liability, as a
result of study, the present inventors have reached a
20   conclusion that it is possible to measure a magnetic
field gradient with high sensitivity by measurement
performed by replacing a difference in minute magnetic
field intensity on the basis of a difference in
measurement position with a difference in polarization
25   rotation angle of a laser beam for a linear
polarization probe.

A principal object of the present invention is

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to provide an atomic magnetometer capable of measuring a magnetic field gradient with high sensitivity.

Another object of the present invention is to provide a magnetic sensing method capable of measuring the magnetic field gradient with high sensitivity.

According to an aspect of the present invention, there is provided an atomic magnetometer comprising:

a light source for a probe beam; and

a medium in which the probe beam is to be propagated,

wherein the medium is a substance which changes a polarization rotation angle of the probe beam depending on a magnetic field intensity at a first measurement position and a magnetic field intensity at a second measurement position different from the first measurement position, and

wherein the atomic magnetometer directly measures a difference between the magnetic field intensity at the first measurement position and the magnetic field intensity at the second measurement position as a difference in polarization rotation angle, along a propagation path of the probe beam.

According to another aspect of the present invention, there is provided a magnetic sensing method for measuring a polarization rotation angle of a probe beam by irradiating an atomic group contained in a

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hollow portion of a cell with a pump beam to
uniformize directions of spin of atoms constituting
the atomic group and then by irradiating the atomic
group uniformized in spin direction of the atoms with
5   linearly polarized light as the probe beam, the
magnetic sensing method comprising:

introducing the probe beam having a direction
(plane) of polarization rotated by a magnetic field
intensity at a first measurement position to a second
10 measurement position different from the first
measurement position so as to permit optical
subtraction of the polarization rotation angle of the
probe beam; and

obtaining information on a difference between
15 a magnetic field intensity at the first measurement
position and a magnetic field intensity at the second
measurement position by measuring the polarization
rotation angle of the probe beam having passed through
the second measurement position.

20   According to a further aspect of the present
invention, there is provided an atomic magnetometer
comprising:

a cell having a hollow portion;

an atomic group contained in the hollow
25 portion of the cell;

a pump beam light source for uniformizing a
direction of spin of a plurality of atoms constituting

the atomic group;

   a light source, for the probe beam, for irradiating the cell with linearly polarized light as the probe beam; and

5   a detector for detecting information on a polarization rotation angle of the linearly polarized light,

   wherein an irradiation direction of the circularly polarized light as a pump beam for the

10   atomic group in the cell and an irradiation direction of the probe beam for the atomic group intersect with each other at a first measurement position, and an irradiation direction of the circularly polarized light as a pump beam for the atomic group in the cell

15   and an irradiation direction of the probe beam for the atomic group having passed through the first measurement position intersect with each other at a second measurement position different from the first measurement position, and

20   wherein the atomic magnetometer is configured to perform optical subtraction between the polarization rotation angle of the probe beam on the basis of the magnetic field intensity at the first measurement position and the polarization rotation

25   angle of the probe beam on the basis of the magnetic field intensity at the second measurement position.

   According to the present invention, it is

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possible to provide a high-sensitivity sensor by
directly measuring a difference between magnetic field
intensities at different two positions as a difference
in polarization rotation angle of the probe beam.

5   These and other objects, features and
advantages of the present invention will become more
apparent upon a consideration of the following
description of the preferred embodiments of the
present invention taken in conjunction with the

10   accompanying drawings.

[BRIEF DESCRIPTION OF THE DRAWINGS]
          Figure 1 is a flow chart for illustrating a
magnetic sensing method according to the present

15   invention.
          Figure 2 is a schematic view for illustrating
Embodiment 1.
          Figure 3 is a schematic view for illustrating
Embodiment 2.

20   Figure 4 is a schematic view for
supplementally illustrating Embodiment 2.
          Figure 5 is a schematic view for illustrating
Embodiment 3.
          Figure 6 is a schematic view for illustrating

25   Embodiment 4.
          Figure 7 is a schematic view for
supplementally illustrating Embodiment 4.

Figure 8 is a schematic view for illustrating Embodiment 5.

Figure 9 is a schematic view for illustrating Embodiment 6.

5   Figure 10 is a schematic view for illustrating Embodiment 7.

Figure 11 is a schematic view for supplementally illustrating Embodiment 7.

Figure 12 is a schematic view for illustrating

10   Embodiment 8.

Figure 13 is a schematic view for illustrating Embodiment 9.

[BEST MODE FOR CARRYING OUT THE INVENTION]

15   (First Embodiment: magnetic sensing method)

The magnetic sensing method according to the present invention in this embodiment will be described with reference to Figure 1.

The magnetic sensing method in this embodiment

20   has the following features.

That is, directions of spin of atoms constituting an atomic group contained in a hollow portion of a cell are uniformized by irradiating the atomic group with a pump beam. Then, the atomic group

25   uniformized in spin direction of the atoms is irradiated with linearly polarized light as a probe beam to measure an angle of rotation of a plane of

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polarization of the probe beam, so that information on

a measured magnetic field intensity is obtained.

In this embodiment, as shown in Figure 1,

first, a direction of polarization of the probe beam

5   is rotated by a magnetic field intensity at a first

measurement position (S1). Then, the probe beam with

the rotated direction of polarization by the magnetic

field intensity at the first measurement position is

guided to a second measurement position so as to

10   permit optical subtraction of polarization rotation

angles of the probe beam (S2). Next, an angle of

rotation of a plane of polarization of the probe beam

having passed through the second measurement position

is measured (S3). As a result, it is possible to

15   obtain information on a difference between magnetic

field intensities at mutually different two positions.

Characteristic elements in the magnetic

sensing method using an atomic magnetometer will be

described in detail.

20   A: Cell

A cell is constituted by a material, such as

glass or plastics, capable of passing a probe beam or

a pump beam through the cell. In the cell, alkali

metal (such as K or Rb) is contained in a gas state as

25   an atomic group or an atomic cluster. If the alkali

metal is placed in the gas state (vaporized) during

the sensing, the alkali metal is not necessarily

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required to be placed in the gas state when the
sensing is not made. For example, potassium (alkali
metal) is placed in a glass cell and is heated at
about 180 °C, so that the glass cell can be filled
5   with vapor of potassium.

The atomic group contained in the cell is not
limited to alkali metal atoms but may also be any
material so long as the sensing method can be
performed by using the material. Further, in the cell,
10   it is also possible to contain buffer gas in addition
to the above-described atomic group. As the atomic
group, in addition to K or Rb, Xe or the like may also
be mixed.

B: Pump beam

15   The pump beam may desirably be consisting of
circularly polarized light itself, i.e., only
consisting of the circularly polarized light but in
this embodiment, inclusion of another polarization
component is not excluded so long as the pump beam
20   includes the circularly polarized light.

The pump beam is used for uniformizing
directions of electron spin of the respective atoms
constituting the atomic group. Specifically, the
electron spin directions can be uniformized by
25   utilizing a phenomenon which is called circular
polarization pumping. By using a right-hand circular
polarization pump beam, directions of spin of atoms

which are directed randomly can be uniformized in a
traveling direction of the pump beam. By using a
left-hand circular polarization pump beam, the
directions of spin of the atoms can be uniformized in
5   a direction opposite to the traveling direction of the
pump beam. The uniformization of the directions of
spin of the atoms means, in a precise sense, that
directions of electro spin are uniformized in the case
where the substance to be contained in the cell is
10   alkali metal and that directions of atomic nuclear
spin (nuclear spin) are uniformized in the case where
the substance is rare (noble) gas.

The reason why the spin directions can be
uniformized as described above is that the circularly
15   polarized light has angular momentum and therefore
based on low of conservation of angular momentum,
there is a spin direction in which light is not
absorbed. Once excited atoms emit beams in random
polarization states by spontaneous emission and can
20   create mutually different ground states. However, by
repeating such pumping, it is possible to finally
uniformize the directions of spin of the respective
atoms constituting the atomic group.

C: Probe beam

25   The probe beam may desirably be detuned from a
resonance frequency of the atoms to some extent in
order to avoid unnecessary pumping or in order to

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avoid absorption. The probe beam may desirably be

consisting only of the linearly polarized light but in

the present invention, inclusion of another

polarization component is not excluded so long as the

5   probe beam includes a linearly polarized light

component.

A device is configured so that an irradiation

direction of the probe beam for the atoms in the cell

and an irradiation direction of the pump beam for the

10   atoms in the cell intersect with each other at

respective measurement positions. The irradiation

directions of the probe beam and the pump beam are not

particularly limited so long as the irradiation

directions intersect with each other but are generally

15   configured to intersect with each other at right

angles.

It is known that a plane of polarization is

rotated by a magneto-optical effect which can be

called Faraday effect in a broad sense including

20   non-linear Faraday effect, Cotton-Mouton effect, and

the like, when the linearly polarized light is

incident on a polarized atomic group with respect to

X-direction. Specifically, an angle of polarization of

the probe beam traveling along the incident direction

25   is rotated in a yz-plane by a measurement magnetic

field which is parallel or perpendicular to the probe

beam. A magnetometer utilizing a change in this angle

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of rotation correspondingly to a magnitude of the
magnetic field has been known.

Also in this embodiment, the polarized atomic
group is formed by the above-described pump beam and

5   the probe beam is directed to the atomic group in the
cell, so that information on a polarization rotation
angle of the probe beam before and after the probe
beam passes through the cell is obtained.

With respect to a light source, an individual

10   light source may be used for each of the pump beam and
the probe beam and it is also possible to create
circularly polarized pump beam and linearly polarized
probe beam by using a common light source and a
polarizing plate or the like. As the light source for

15   outputting the pump beam and the probe beam, a laser
light source can be used. For example, in the case of
using potassium as the atomic group or the atomic
cluster in the cell, a laser light source with a
wavelength of about 770 nm detuned in a range from

20   0.02 nm to 1 nm can be utilized.
D: Obtainment of information on angle of rotation of
plane of polarization of probe beam

Information on an angle of rotation of a plane
of polarization (or a direction of polarization) can,

25   e.g., be obtained by detecting a probe beam having
passed through the above-described cell with a
photo-diode array through the polarizing plate. It is

also possible to appropriately employ means other than
the detecting means (the photo-diode array) so long as
the information can be obtained by the means.

Specifically, the polarization rotation angle
of the probe beam is detected by a crossed nicol
polarimeter or a balanced polarimeter. Details are
shown in Embodiments appearing hereinafter.
E: Method of performing optical subtraction (optical
computing (operation))

In the case where differential information on
magnetic field intensity at mutually differential two
measurement positions (including the case where these
two measurement positions are located in not only the
same cell but also different cells) are obtained by
the magnetic sensing method using the atomic
magnetometer, the following factors (1) to (4) are
appropriately combined for each of the measurement
positions.

(1) Direction of the circularly polarized light
as the pump beam incident on the measurement position

(2) Rotational direction of the circularly
polarized light as the pump beam (right-hand
circularly polarized light or left-hand circularly
polarized light)

(3) Direction of the probe beam incident on the
measurement position

(4) Presence or absence of an operation with

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respect to a polarization rotation angle of the probe

beam

(Second Embodiment: atomic magnetometer)

An atomic magnetometer in this embodiment has

the following features.

Specifically, the atomic magnetometer includes

a cell having a hollow portion, an atomic group

contained in the hollow portion, and a pump beam light

source for uniformizing directions of spin of a

plurality of atoms constituting the atomic group. The

atomic magnetometer further includes a probe beam

light source for irradiating the cell with linearly

polarized light as the probe beam, and a detector for

detecting information on an angle of rotation of a

plane of polarization of the linearly polarized light.

With respect to the atomic group in the cell,

an irradiation direction of the circularly polarized

light providing the pump beam and an irradiation

direction of the probe beam are configured to

intersect with each other at a first measurement

position.

Then, with respect to the atomic group in the

cell, an irradiation direction of the circularly

polarized light providing the pump beam and an

irradiation direction of the probe beam having passed

through the first measurement position are configured

to intersect with each other at a second measurement

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position. Further, a polarization rotation angle of the probe beam by a magnetic field intensity at the first measurement position and a polarization rotation angle of the probe beam by a magnetic field intensity

5   at the second measurement position are configured to be subjected to optical subtraction.

Specifically, as a constitution for performing the optical subtraction, the following constitutes (1) to (4) may be employed but the present invention is

10   not limited to the constitutions (1) to (4).

(1) The first measurement position and the second measurement position are located in a first cell and a second cell, respectively, and a half-wave plate configured to pass the probe beam therethrough is

15   provided between the first cell and the second cell (Figure 2).

(2) The first measurement position and the second measurement position are located in the cell, and optical path converting means for passing the probe

20   beam, having passed through the first measurement position, through the second measurement position with an opposite traveling direction is provided (Figures 3 and 4).

(3) The first measurement position and the second

25   measurement position are located in the cell, and both of the circularly polarized light for irradiation at the first measurement position and the circularly

polarized light for irradiation at the second

measurement position are either one of right-hand

circularly polarized light and left-hand circularly

polarized light, and the circularly polarized light

5   for irradiation at the first measurement position and

the circularly polarized light for irradiation at the

second measurement position have traveling directions

opposite from each other (Figure 5).

(4) The first measurement position and the second

10   measurement position are located in the cell, and the

circularly polarized light for irradiation at the

first measurement position and the circularly

polarized light for irradiation at the second

measurement position have polarization directions

15   opposite from each other and have the same traveling

direction (Figure 6).

In this embodiment, the atomic magnetometer

may also be configured to have a measurement position

which is different from the first measurement position

20   and the second measurement position which are located

in the same cell (Figures 7, 8 and 10).

Further, the atomic magnetometer may also be

configured to pass laser light from the pump beam

light source through a member including a polarization

25   element for equalizing a light intensity of right-hand

circularly polarized light with a light intensity of

left-hand circularly polarized light and then to pass

circularly polarized light through the cell (Figures 9
and 10).

Further, in this embodiment, as the cell in
which the atomic group is incorporated, it is also

5   possible to use different cells depending on the
respective measurement positions. Further, a plurality
of measurement positions different from each other may
be located in the same cell. However, in the case of
using the different cells, it is preferable that the

10   type and an amount of the atomic group to be
incorporated in each of the cells are strictly
uniformized.
(Third Embodiment: magnetometer)

The above-described First Embodiment and

15   Second Embodiment are explained on the premise that
the circularly polarized light is used as the pump
beam but as shown below, the pump beam is not always
required.

Specifically, a magnetometer in this

20   embodiment is provided with a light source for a probe
beam and a medium through which the probe beam is
configured to propagate.

The medium is a substance which changes a
polarization rotation angle depending on a magnetic

25   field intensity at a first measurement position and a
magnetic field intensity at a second measurement
position and may specifically be vapor of alkali metal

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such as potassium or cesium. Further, rare gas (noble

gas) such as helium or xenon may also be utilized.

Further, it is also possible to employ substances,

such as magnetic materials including Fe, Co, Ni,

5   Y_3Fe_{12}, MnSb, MnBi, $YFeO_3$, $NdFe_3$, $CrBr_3$, EuO, $CdCv_2S_4$,

etc., and glass and the like. Further, a (magnetic

field) gradiometer can also be realized by directly

measuring a difference between a magnetic field

intensity at the first measurement position and a

10   magnetic field intensity at the second measurement

position in the medium along a propagation path of the

probe beam.

       These constitutions are described in detail in

Embodiments 8 and 9 appearing hereinafter.

15   Hereinbelow, the present invention will be

described based on specific embodiments.

(Embodiment 1)

       Figure 2 is a schematic view showing a

characterizing portion of Embodiment 1 of the present

20   invention.

       Referring to Figure 2, reference symbols 1a

and 1b represent a laser beam for circular

polarization pumping, a reference numeral 2 represents

a laser beam for linear polarization probe (probe

25   beam), and a reference numeral 3 schematically

illustrates alkali metal vapor or rare gas as

precession of spin.

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In cells 4a and 4b, alkali metal vapor or rare gas is filled. Further, in Figure 2, Helmholtz coils 6a and 6b for cancelling a static magnetic field in z-axis direction or applying a bias magnetic field in z-axis direction are schematically illustrated. By providing Helmholtz coils also with respect to y-axis direction and x-axis direction, three-axis Helmholtz coils (not shown) may also be employed.

A first measurement position 11 is located in the cell 4a and a second measurement position 12 is located in the cell 4b. Polarizing plates 13 and 14 are disposed at positions so that polarizing axes are perpendicular to each other, i.e., are disposed at crossed nicol positions. A Faraday modulator 15 is used for imparting minute vibration of an angle of rotation to a probe beam. A photo-detector 16 is constituted by a photo-diode or the like. A temperature control oven 9 keeps a temperature of the alkali metal cells 4a and 4b at a constant temperature. In the oven 9, a half-wave plate 23 is disposed. When an angle of rotation of a plane of polarization of the probe beam (linearly polarized light) having passed through the first measurement position 11 is $+\varphi$ with respect to a crystal axis of the half-wave plate 23, the rotation angle is inverted in sign to $-\varphi$ with respect to the crystal axis of the half-wave plate 23 after the probe beam passes through the half-wave

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plate 23.

A magnetic field intensity (magnetic flux density) in y-axis direction at the first measurement position 11 is taken as $By1$ and a magnetic field

5   intensity in y-axis direction at the second measurement position 12 is taken as $By2$.

A magnetometer in this embodiment includes the probe beam, a medium which changes a polarization rotation angle depending on a magnetic field intensity

10   during propagation of the probe beam, and the first and second measurement positions for the medium. The magnetometer is characterized in that a difference between the magnetic field intensity at the first measurement position and the magnetic field intensity

15   at the second measurement position is directly measured as a difference in polarization rotation angle along a propagation path of the probe beam.

In this embodiment, in an atomic magnetometer using the probe beam and alkali metal vapor or rare

20   gas, such a constitution that the cells 4a and 4b, the probe beam 2, and the first and second measurement positions 11 and 12 are used is adopted. By directly measuring a difference between the magnetic field intensities at the first and second measurement

25   positions, i.e., $(By2 - By1)$ as a difference in polarization rotation angle $(\varphi2 - \varphi1)$, a high-sensitivity sensor suppressing mixing of noise

due to a difference between photo-sensors is provided.

Particularly, in this embodiment, the
half-wave plate 23 is used to invert a polarization
rotation different after the probe beam passes through
the first cell 4a and then the probe beam passes
through the second cell 4b. As a result, the magnetic
field intensity difference (By2 - By1) between the
first and second measurement positions 11 and 12 is
directly measured as the polarization rotation angle
difference ($\varphi2 - \varphi1$) to provide the high-sensitivity
magnetometer which has suppressed the mixing of noise
due to the difference between the photo-sensors.

The atomic magnetometer which performs
magnetic measurement by incidence of the circularly
polarized laser light (the pump beam) and the probe
beam on the cell in which the alkali metal vapor or
the like is filled is based on the following principle.
The atomic magnetometer measures rotation of spin of
electron excited by the circularly polarized laser
beam (the pump beam) in a measurement magnetic field
with macro magnetization as rotation of the incident
linearly polarized light as the probe beam with
respect to a polarization direction and thus is
capable of measuring a static magnetic field or an
oscillating magnetic field with high sensitivity.

In an xyz coordinate system shown in Figure 2,
first, a system in which the circularly polarized

laser lights 1a and 1b are emitted in z-axis direction,

the probe beam (the linearly polarized light) is

emitted in x-axis direction, and a magnetic field By

to the measured is present in y-axis direction is

5   considered. In this case, a macro magnetization vector

m = (mx, my, mz) of the electron spin is represented

by the following optical Bloch equation:

$$d\mathbf{m}/dt = \mathbf{\Omega} \times \mathbf{m} - \gamma_{eff}\mathbf{m} + \mathbf{P} \quad \ldots \ldots \quad (1)$$

As described above, m = (mx, my, mz)

10   represents the macro magnetization of the excited

electron spin and ω (0, ωeff, 0) is a parameter with

respect to the magnetic field. P = (0, 0, P)

represents a parameter with respect to the pump beam

and γeff represents a parameter with respect to

15   relaxation. Further, ωeff = γeBy/Q, γeff = (R_{SD} +

R_P)/Q, P = R_P/Q, and γe = g&mYB/h are satisfied. Q is

a slow down factor, h is a Planck constant, (= 2.0023)

is g-factor, R_P is an optical pumping rate, R_{SD} is a

spin relaxation rate, and μB is Bohr magneton.

20   In the case where By is the static magnetic

field, a stationary solution of the equation (1) is,

from dm/dt = 0, as follows:

     (mx,my,mz)=(PΩeff/(Ωeff^2+γeff^2),0,-Pγeff/

(Ωeff^2+γeff^2))   ...(2).

25   In this case, with respect to the probe beam

which is the linearly polarized light propagating in

x-axis direction, a polarization rotation angle φ by a

magnetic field with respect to its polarization

direction when a right-hand screw rotation direction

is taken as a positive direction with respect to

5   x-axis direction is represented by the following

equation:

$$\varphi \ (=\pi L(n^+ - n^-)/\lambda) = 2\pi Lmx(n0-1)/\lambda ... (3).$$

In the equation (3), L represents a

propagation distance, λ represents a wavelength, n^+

10   and n^- represent a refractive index with respect to

right-hand circularly polarized light and a refractive

index with respect to left-hand circularly polarized

light, respectively, and n0 represents a refractive

index of a medium in the case of no spin polarization.

15   From the equations (2) and (3), when the

magnetic field By is weak and the approximation: ωeff

<< γeff can be made, the polarization rotation angle

by the static magnetic field is represented as

follows:

20       $\varphi = \alpha ABy ... (4).$

$\alpha A = 2\pi L(n0-1)P\gamma e/(\lambda Q\gamma eff^2) ... (5).$

Therefore, the rotational direction of the

polarization rotation angle φ depends on a sign of mx

($= P\omega/\gamma eff P^2$), thus finally depending on a sign of PBy.

25   The sign of P = Rp/Q is positive for the right-hand

circularly polarized light in z-axis direction,

negative for the left-hand circularly polarized light

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in z-axis direction, negative for the right-hand

circularly polarized light in -z-axis direction, and

positive for the left-hand circularly polarized light

in -z-axis direction.

5   In Embodiment1, between the polarizing plates

13 and 14 disposed so that their polarization

transmission axis directions intersect each other at

right angles, a minute oscillation angle F (=

$\Delta\varphi F0\exp[-i\omega Ft]$ is provided by the Faraday modulator 15.

10   Then, from the oscillation angle F providing a dark

state, a polarization rotation angle by the alkali

metal vapor cell between the polarizing plates is

measured. The Faraday modulator has an angular

frequency ωF. When an initial polarization rotation

15   angle after the probe beam 2 is changed into linearly

polarized light by the polarizing plate 13 is $\varphi0$ (= 0)

with respect to the crystal axis of the half-wave

plate 23, the probe beam is rotated $\varphi1$ (= $\alpha ABy1$) in

the cell 4a. For that reason, the polarization

20   rotation angle after the probe beam passes through the

cell 4a is $\varphi F + \varphi0 + \varphi1$.

         Then, the half-wave plate 23 shifts a phase by

π(rad), so that the sign of the polarization rotation

angle is inverted with respect to the crystal angle of

25   the half-wave plate 23 after the probe beam passes

through the half-wave plate 23. As a result, the

polarization rotation angle is $-(\varphi F + \varphi0 + \varphi1)$. Then,

the probe beam is rotated φ2 (= αABy2) in the cell 4b,

so that the polarization rotation angle after the

probe beam passes through the cell 4b is -(φF + φ0 +

φ1 - φ2). Therefore, from the oscillation angle φF

providing the dark state, a polarization rotation

angle (-φ0 - φ1 + φ2) by the alkali metal vapor cell

between the polarizing plates is measured. When φ0 =

0, the difference in magnetic field intensity can be

directly measured as a difference (φ2 - φ1) in

polarization rotation angle. Further, even when φ0 is

not zero, φ0 is constant, so that the difference in

magnetic field intensity can be directly measured as

the difference in polarization rotation angle.

Here, a conventional atomic magnetometer

constituting a gradiometer by measuring values of φ1

and φ2 separately by polarization rotation meters

(polarimeters) will be considered.

As the polarimeter, similarly as in Embodiment

1, when the crossed nicol polarization consisting of

the pair of polarizing plates, the Faraday modulator,

and the photo-sensor is considered, the conventional

atomic magnetometer requires two polarimeters.

The polarimeter is generally a device for

providing a signal V (= βφ) to a polarization rotation

angle φ and with respect to this signal V, a

measurement magnetic field By is obtained as By-qV (=

qβφ1) where q and β are constants of proportionality.

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Particularly, β is the constant of
proportionality depending on a characteristic of the
polarimeter or the photo-sensor constituting the
polarimeter. When constants of proportionality of the
two polarimeters are β1 and β2, signals are V1 and V2,
and signal noises resulting from the photo-sensor or
the like are δV1 and δV2, the two signals V1 and V2
are V1 = β1φ1 + δV1 and V2 = β2φ2 + δV2. Incidentally,
δV2 has the same order as δV1 and δV. Therefore, a
difference between a magnetic field intensity at the
first measurement position and a magnetic field
intensity at the second measurement position (ΔBy21 =
By2- By1) is represented by the following equation:

$$\Delta By21 = (q\beta 2\varphi 2 - q\beta 1\varphi 1) + q(\delta V2 - \delta V1) \ldots (6).$$

With respect to the second term of this
equation (6), δV2 and δV1 are different in phase, so
that q(δV2 − δV1) has the same order as qδV.

Further, from the first term of the equation
(6), in the case where φ1 and φ2 are very close to
each other, it is understood that the magnetic field
intensity difference between the first and second
measurement positions (ΔBy21 = By2 − By1) cannot be
accurately measured in a strict sense unless β1 and β2
are ideally equal to each other.

On the other hand, in the present invention in
which the magnetic field intensity difference between
the first and second measurement positions (By21 =

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By2 - By1) is directly measured as the difference in
polarization rotation angle ($\varphi2 - \varphi1$), a single (only
one) polarimeter is used. Therefore, it is understood
that the magnetic field intensity difference can be

5   measured with accuracy even in the case of a small
difference in polarization rotation angle ($\varphi2 - \varphi1$),
from the following equation:

$$\Delta By2\dot{1}=q\beta(\varphi2-\varphi1)+q\delta V\ldots(7).$$

In Embodiment 1, the crossed nicol polarimeter

10 is used but it is also possible to use the balanced
polarimeter.

In the present invention, when the crossed
nicol polarimeter is used, the number of photo-sensors
can be decreased from two to one. Further, when the

15 balanced polarimeter is used, the number of
photo-sensors can be decreased from four to two. In
Embodiment 1, as the alkali metal, potassium is used
but it is also possible to similarly user rubidium,
cesium, and the like. The present invention is also

20 similarly applicable to an ordinary atomic
magnetometer using alkali metal gas or rare gas.

In this embodiment, the case of the weak
magnetic field is described but is understood that the
present invention is also similarly applicable to the

25 case of a strong magnetic field. Further, in this
embodiment, the static magnetic field measurement or
the like of a low frequence to the extent that the

magnetic field can be regarded as the static magnetic

field is described but the present invention achieves

a similar effect with respect to oscillating magnetic

field measurement.

The oscillating magnetic field measurement

will be described below. In the case where By

represents an oscillating magnetic field with an

angular frequency ω, By is defined as By = $By0e^{-i\omega t}$

and then a forced vibration (oscillation) solution is

obtained. Further, when an angular frequency by a bias

magnetic field for resonance Bz0 applied with respect

to z-axis direction is $\omega0$ and a real part of mx is S,

the following equation is satisfied.

S = γeff mzγeBy0 cos(ωt)/(Q(($\omega-\omega0$)^2 +

γeff^2))))...(8).

In this case, a polarization rotation angle φ

by a magnetic field with respect to a polarization

direction of the probe beam which is linearly

polarized light propagating in x-axis direction when a

direction of a right-hand screw is taken as a positive

direction with respect to x-axis direction can be

represented by the following equation:

φ=0.5LrecfD1nS[-DD1(ν)+DD2(ν)]...(9).

In the equation (9, ν represents a frequency

of the probe beam, n represents an atomicity density,

c represents a light velocity, and re (= 2.82 x 10^{-15}

m) represents classical electron radius.

In this embodiment, potassium (K) is used for

the alkali metal vapor, fD1 is 1/3, and the term

[-DD1(ω) + DD2(ω)] shows a dispersion relationship

between D1 line and D2 line of potassium in

5   consideration of wavelength dispersion of the D1 line

and the D2 line. Therefore, from the equations (8) and

(9), the polarization rotation angle for the

oscillating magnetic field is represented by the

following equations:

10   φ =αB By0...(10).

         αB=0.5LrecfD1n[-DD1(ω)+DD2(ω)]γeff mzγeBy0

cos(ωt)/(Q((ω-ω0)^2 + γeff^2))...(11).

         Accordingly, it is understood that the

rotational direction of φ depends on the sign of

15   mzBy0cos (ωt). The sign of mz is positive for the

right-hand circularly polarized light in z-axis

direction, negative for the left-hand circularly

polarized light in z-axis direction, negative for the

right-hand circularly polarized light in -z-axis

20   direction, and positive for the left-hand circularly

polarized light in -z-axis direction. Further,

compared with a period T = 2Π/w, a time period in

which the light passes through the cells 4a and 4b at

the light velocity c is negligible, so that it is

25   considered that cos(ωt) at the passing of light

through the cell 4a is identical to that at the

passing of light through the cell 4b.

Therefore, the polarization angle after the
light passes through the cells 4a and 4b and the
half-wave plate is represented by the following
equation:

5          $\Delta\varphi=\varphi2-\varphi1=\alpha B(By02-By01)...(12)$,
wherein $By1=By01e^{-i\omega t}$ and $By2=By02e^{-i\omega t}$.

As described above, also in the case of the
oscillating magnetic field measurement, it is
understood that a high-sensitivity atomic magnetometer

10   which suppresses the mixing of noise due to the
difference between the photo-sensors can be provided
by directly measuring the magnetic field intensity
difference $(By2 - By1)$ as the polarization rotation
angle difference $(\varphi2 - \varphi1)$.

15   (Embodiment 2)

Figure 3 is a schematic view showing a
characterizing portion of Embodiment 2 of the present
invention.

Referring to Figure 3, reference numeral 1

20   represents a circularly polarized laser beam, a
reference numeral 2 represents a laser beam for probe
(probe beam), and a reference numeral 3 schematically
illustrates alkali metal vapor or rare gas as
precession of spin.   In a cell 4, alkali metal vapor or

25   rare gas is filled.   Further, in Figure 2, three-axis
Helmholtz coils 6a and 6b for cancelling a static
magnetic field or applying a bias magnetic field in

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z-axis direction are schematically illustrated.

A first measurement position 11 and a second
measurement position 12 are located in the cell 4.
Polarizing plates 13 and 14 are disposed at crossed

5   nicol positions. An atomic magnetometer in this
embodiment further includes a Faraday modulator 15, a
photo-detector 16, a temperature control oven 9 for
keeping a temperature of the alkali metal cell 4 at a
constant temperature, and a polarization-maintaining

10   fiber 20 as a polarization-maintaining optical path
fold-back means.

In this embodiment, the atomic magnetometer
using the circularly polarized laser beam 1, the probe
beam 2, and the alkali metal vapor is characterized by

15   the following constituents.

That is, the atomic magnetometer includes the
cell 4 in which the alkali metal vapor is filled, the
circularly polarized laser beam (circularly polarized
light) 1 for exciting the alkali metal vapor, the

20   probe beam 2 emitted perpendicularly to the circularly
polarized light 1, and the polarization-maintaining
optical path fold-back means 20. Then, the probe beam
2 passes through the second measurement position 12
after it passes through the first measurement position

25   11 and the optical path of the probe beam 2 is folded
back by using the polarization-maintaining optical
path fold-back means 20. Thus, the magnetic field

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intensity difference between the first and second

measurement positions (By2 - By1) is directly measured

as the polarization rotation angle difference

(φ2 - φ1). As a result, a high-sensitivity atomic

5   magnetometer which suppresses the mixing of noise due

to the difference between the photo-sensors is

provided.

In Embodiment 1, the sign inversion operation

of φ1 is performed but in this embodiment (Embodiment

10   2), the sign inversion operation of φ1 is performed by

using the polarization-maintaining optical path

fold-back means 20, so that (arithmetic) processing of

the difference in polarization rotation angle is

performed.

15   Now, an initial polarization rotation angle

after the probe beam 2 is changed into circularly

polarized light by the Polarizing late 14 is taken as

φ0 (= 0) when the right-hand screw direction is taken

as positive with respect to x-axis direction. The

20   probe beam 2 passes through the first measurement

position 11 in the cell 4 to be rotated φ1 (= αABy1),

so that the polarization rotation angle is φF + φ0 +

φ1. In this case, as described in Embodiment 1, φf is

the minute angle of oscillation φF (= ΔφF0exp[-iωFt])

25   provided by the Faraday modulator 15 between the

polarizing plates 13 and 14.

The probe beam 2 having passed through the

cell 4 is thereafter folded back toward -x-axis direction by using the polarization-maintaining optical path fold-back means 20 to have a polarization direction symmetrical with respect to the y-axis, so

5   that the sign of the polarization rotation angle is inverted to result in a polarization rotation angle of $-(\varphi + \varphi 0 + \varphi 1)$.

Further, for the fold-back probe beam, the pump beam is emitted in z-axis direction with respect

10   to a traveling direction (-x-axis direction) of the probe beam, so that the rotational direction of the polarization rotation angle is inverted with respect to the traveling (-x-axis) direction. However, with respect to x-axis direction, the probe beam is still

15   rotated in the right-hand screw direction, so that the probe beam passes through the second measurement position 12 to be rotated $+\varphi 2$ (= $\alpha ABy2$).

Therefore, after the probe beam passes through the second measurement position 12, the polarization

20   rotation angle is $-(\varphi F + \varphi 0 + \varphi 1 - \varphi 2)$. That is, similarly as in Embodiment 1, it is possible to provide a high-sensitivity magnetometer having suppressed the mixing of noise due to the difference between the photo-sensors by directly measuring the

25   magnetic field intensity difference (By2 - By1) between the first and second measurement positions 11 and 12 as the polarization rotation angle difference

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($\varphi2 - \varphi1$).

In Figure 3, as the polarization-maintaining optical path fold-back means 20, the polarization-maintaining fiber is used but it is also

5   possible to use a polarization-maintaining optical path fold-back means 20b constituted by two mirrors 17 and 18 and a phase adjusting plate 19.

The phase adjusting plate 19 is used to correct elliptically polarized light, by reflection

10 principally due to dielectric loss of the mirrors 17 and 18, to linearly polarized light but in the case where polarization reflection characteristic of the mirrors 17 and 18 is regarded as being good, the phase adjusting plate 19 can be omitted a minute

15 polarization rotation angle φM which is regarded as a constant value based on the reflection characteristic of the mirrors can be added but the polarization rotation angle φM is the constant value, thus being no problem. As the mirrors 17 and 18, particularly, by

20 using a multilayer reflection mirror, it is possible to design the mirrors so that the elliptically polarized light is suppressed and the polarization direction is inverted by fold-back similarly as in the case of the above-described polarization-maintaining

25 fiber.

(Embodiment 3)

Figure 5 is a schematic view for illustrating

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Embodiment 3 of the present invention.

In this embodiment, an atomic magnetometer using the pump beam, the probe beam and the alkali metal vapor is characterized by the following
5   constituents.

The atomic magnetometer includes an alkali metal vapor 3, a cell in which the alkali metal vapor 3 is filled, first and second pump beams 1a and 1c for polarizing electron spin of the alkali metal vapor 3
10   at different positions, and a probe beam 2 emitted perpendicular to the first and second pump beam 1a and 1c.

The first and second pump beam 1a and 1c are emitted in directions opposite from each other and
15   then the probe beam passes through a first measurement position 11 for the first pump beam 1a and thereafter passes through a second measurement position 12 for the second pump beam 1c. By directly measuring a magnetic field intensity difference (By2 - By1)
20   between the first and second measurement positions 11 and 12 as a polarization rotation angle difference (φ2 - φ1), a high-sensitivity magnetometer having suppressed the mixing of noise due to the difference between the photo-sensors is provided.

25   More specifically, as shown in Figure 5, the first pump beam which is right-hand circularly polarized light is directed to the first measurement

position 11 in z-axis direction and the second pump

beam which is right-hand circularly polarized light is

directed to the second measurement position 12

in -z-axis direction. The linearly polarized probe

5   beam is directed to the first and second measurement

positions 11 and 12 in x-axis direction.

As described in Embodiment 1, when the

incident direction of the circularly polarized pump

beam is inverted, the rotational direction of the

10   polarization rotation angle with respect to the

magnetic field is inverted. Thus, the probe beam

passes through the first and second measurement

positions excited by the oppositely directed pump

beams, so that optical subtraction of the polarization

15   rotation angles can be performed.

Now, an initial polarization rotation angle

after the probe beam 2 is changed into circularly

polarized light by the Polarizing late 14 is taken as

$\varphi 0$ when the right-hand screw direction is taken as

20   positive with respect to x-axis direction. The probe

beam 2 passes through the first measurement position

11 in the cell 4 to be rotated $\varphi 1$ (= $\alpha ABy1$), so that

the polarization rotation angle is $\varphi F + \varphi 0 + \varphi 1$.

Further, the probe beam 2 passes through the

25   second measurement position 12 different in pump beam

traveling direction in the cell 4 to be rotated $-\varphi 2$

(= $-\alpha ABy2$). Therefore, after the probe beam 2 passes

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through the second measurement position 12, the

polarization rotation angle is (φF + $\varphi 0$ + $\varphi 1$ - $\varphi 2$).

Similarly as in Embodiment 1, Embodiment 3 has such an

effect that it is possible to provide a

5   high-sensitivity magnetometer having suppressed the

mixing of noise due to the difference between the

photo-sensors by directly measuring the magnetic field

intensity difference ($By2$ - $By1$) between the first and

second measurement positions 11 and 12 as the

10   polarization rotation angle difference ($\varphi 2$ - $\varphi 1$).

In Figure 5, codirectional Helmholtz coils 6a,

6b, 6c and 6d for performing resonance measurement of

the oscillating magnetic field by applying bias

magnetization permits resonance measurement with

15   subtraction processing. Further, in Figure 5,

reference numerals or symbols identical to those in

·Figures 1 to 3 represents means or portions having the

same functions as those shown in Figures 1 to 3.

(Embodiment 4)

20   Figure 6 is a schematic view for illustrating

Embodiment 4 of the present invention.

In this embodiment, an atomic magnetometer

using the pump beam, the probe beam and the alkali

metal vapor is characterized by the following

25   constituents.

The atomic magnetometer includes an alkali

metal vapor 3, a cell in which the alkali metal vapor

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3 is filled, first and second pump beams 1a and 1d for
polarizing electron spin of the alkali metal vapor 3
at different positions, and a probe beam 2 emitted
perpendicular to the first and second pump beam 1a and
5   1d.

The first and second pump beam 1a and 1d are
directed so as to be opposite in rotational direction
of circularly polarized light from each other and then
the probe beam passes through a first measurement
10 position 11 for the first pump beam 1a and thereafter
passes through a second measurement position 12 for
the second pump beam 1d. By directly measuring a
magnetic field intensity difference (By2 - By1)
between the first and second measurement positions 11
15 and 12 as a polarization rotation angle difference
(φ2 - φ1), a high-sensitivity magnetometer having
suppressed the mixing of noise due to the difference
between the photo-sensors is provided.

More specifically, as shown in Figure 6, the
20 first pump beam which is right-hand circularly
polarized light is directed to the first measurement
position 11 in z-axis direction and the second pump
beam which is left-hand circularly polarized light is
directed to the second measurement position 12 in
25 z-axis direction. The linearly polarized probe beam is
directed to the first and second measurement positions
11 and 12 in x-axis direction.

As described in Embodiment 1, when the
circular polarization rotational direction of the
circularly polarized pump beam is inverted, the
rotational direction of the polarization rotation

5   angle with respect to the magnetic field is inverted.
Thus, the probe beam passes through the first and
second measurement positions excited by the oppositely
directed pump beams with the opposite circular
polarization rotational directions, so that optical

10 subtraction of the polarization rotation angles can be
performed.

Now, an initial polarization rotation angle
after the probe beam 2 is changed into circularly
polarized light by the Polarizing late 14 is taken as

15 φ0 when the right-hand screw direction is taken as
positive with respect to x-axis direction. The probe
beam 2 passes through the first measurement position
11 in the cell 4 to be rotated φ1 (= αABy1), so that
the polarization rotation angle is φF + φ0 + φ1.

20   Further, the probe beam 2 passes through the
second measurement position 12 different in circular
polarization rotational direction of the pump beam in
the cell 4 to be rotated -φ2 (= -αABy2). Therefore,
after the probe beam 2 passes through the second

25 measurement position 12, the polarization rotation
angle is (φF + φ0 + φ1 - φ2). Similarly as in
Embodiment 1 and Embodiment 3, it is possible to

40

provide a high-sensitivity magnetometer having

suppressed the mixing of noise due to the difference

between the photo-sensors by directly measuring the

magnetic field intensity difference (By2 - By1)

5   between the first and second measurement positions 11

and 12 as the polarization rotation angle difference

(φ2 - φ1).

In Figure 5, two pairs of Helmholtz coils 6a,

6b, 6c and 6d are used but these Helmholtz coils 6a,

10   6b, 6c and 6d may also be replaced with a pair of

Helmholtz coils 6a and 6b as shown in Figure 7.

Further, in Figure 6 and 7, reference numerals or

symbols identical to those in Figures 1 to 3

represents means or portions having the same functions

15   as those shown in Figures 2 to 4.

(Embodiment 5)

Figure 8 is a schematic view for illustrating

Embodiment 5 of the present invention.

In this embodiment, particularly, an atomic

20   magnetometer using the probe beam and the alkali metal

vapor or the rare gas includes a cell 4 in which the

alkali metal vapor or the rare gas is filled, a

plurality of measurement positions 76a to 76d, and a

probe beam 2 configured to pass through the plurality

25   of the measurement positions 76a to 76d. A

high-sensitivity sensor having suppressed the mixing

of noise due to the difference between the

photo-sensors is provided by directly measuring
amounts of high-order gradient of magnetic field
intensity at the plurality of the measurement
positions 76a to 76d as amounts of optical processing

5   of polarization rotation angle of the probe beam 2.

Specifically, as shown in Figure 8, a
right-hand circularly polarized pump beam is directed
to the measurement positions 76a and 76d with respect
to z-axis direction and a left-hand circularly

10   polarized pump beam is directed to the measurement
positions 76b and 76c with respect to z-axis direction.
The probe beam 2 which has been linearly polarized is
directed to the measurement positions 76a to 76d with
respect to x-axis direction.

15   As described in Embodiment 1, when a circular
polarization rotational direction of the circularly
polarized pump beam is inverted, a rotational
direction of a polarization rotation angle with
respect to the magnetic field is inverted. The probe

20   beam 2 successively passes through the measurement
positions 76a to 76d excited by the pump beam for
right-hand circular polarization, left-hand circular
polarization, left-hand circular polarization and
right-hand circular polarization, respectively. As a

25   result, a high-order gradient of magnetic field
intensity $(By4 - By3 - By2 + By1)/(dx)^2$ at the
plurality of measurement positions can be measured

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directly as an optical processing amount of
polarization rotation angle ($\varphi 4 - \varphi 3 - \varphi 2 + \varphi 1$). In
this case, $\varphi 4$, $\varphi 3$, $\varphi 2$ and $\varphi 1$ represent polarization
rotation angles of the probe beam corresponding to

5   magnetic fields By4, By3, By2 and By1, respectively.
The gradient satisfies: $(By4 - By3 - By2 + By1)/(dx)^2$
$= ((By4 - By3)/dx - (By2 - By1)/dx))/dx$, thus being
secondary gradient at the measurement position.

By constituting such an n-order gradiometer,

10   it is possible to eliminate (n-1)-order noise gradient,
so that a sensor suitable for measurement of
biological information or the like can be constituted
by less photo-detecting devices.
(Embodiment 6)

15   Figure 9 is a schematic view for illustrating
Embodiment 6 of the present invention.

Embodiment 6 is the same as Embodiment 5
except that the secondary gradiometer is constituted
by three measurement positions 86a, 86b and 86c.

20   Specifically, as shown in Figure 9, a
right-hand circularly polarized pump beam is directed
to the measurement positions 86a and 86c with respect
to z-axis direction with a width w (< 2dx) and a
left-hand circularly polarized pump beam is directed

25   to the measurement position 86b with respect to z-axis
direction with a width 2w (< 2dx). The probe beam 2
which has been linearly polarized is directed to the

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measurement positions 86a to 86c with respect to

x-axis direction.

As described in Embodiment 1, when a circular

polarization rotational direction of the circularly

5   polarized pump beam is inverted, a rotational

direction of a polarization rotation angle with

respect to the magnetic field is inverted. The probe

beam 2 successively passes through the measurement

positions 86a to 86c excited by the pump beam for

10 right-hand circular polarization, left-hand circular

polarization and right-hand circular polarization,

respectively. As a result, a high-order gradient of

magnetic field intensity $(By3 - 2By2 + By1)/(dx)^2$ at

the plurality of measurement positions can be measured

15 directly as an optical processing amount of

polarization rotation angle $(\varphi4 - \varphi3 - \varphi2 + \varphi1)$. In

this case, $\varphi3$, $\varphi2$ and $\varphi1$ represent polarization

rotation angles of the probe beam corresponding to

magnetic fields By3, By2 and By1, respectively. The

20 gradient satisfies: $(By3 - 2By2 + By1)/(dx)^2 =$

$((By3 - By2)/dx - (By2 - By1)/dx))/dx$, thus being

secondary gradient at the measurement position.

(Embodiment 7)

Figure 10 is a schematic view for illustrating

25 Embodiment 7 of the present invention.

In this embodiment, particularly, an optical

gradiometer is constituted by using a device 99

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including a plurality of polarizing elements 93a and

93b, which have polarization angles different by 90

degrees from each other, disposed in an array on a

substrate to constitute a minute array for right-hand

5   circular polarization and left-hand circular

polarization so that optical processing can be

performed. By this constitution, compared with the

case where an independent polarizing element is held

in a polarizing plate holder and is independently

10   disposed, an apparatus can be simplified and downsized.

Further, the constitution in this embodiment is

suitable for microfabrication by the use of MEMS

(micro electro mechanical system) technique or the

like.

15   Specifically, the device 99 includes a pair of

glass substrates 91 and 95 between which a film-like

polarizing element 92 for adjusting polarization,

film-like polarizing elements 93a and 93b with

polarization angles different by 90 degrees from each

20   other, and a 1/4 (quarter)-wave plate 94 are

sandwiched. By such a constitution, a minute

right-hand circular polarization/left-hand circular

polarization array can be prepared. More specifically,

the polarization direction of the polarizing element

25   92 is y-axis direction, the polarization direction of

the polarizing element 93a is +45 degrees from y-axis

direction toward z-axis direction when a right-hand

screw direction is taken as a positive direction, and
the polarization direction of the polarizing element
93b is -45 degrees from y-axis direction toward z-axis
direction. The polarizing element 92 has the function
5   of equalizing light intensities of right-hand
circularly polarized light and left-hand circularly
polarized light which are created by passing of a pump
beam (laser beam) 97 through the polarizing elements
93a and 93b and the 1/4-wave plate 94, irrespective of
10 a polarization state of the pump beam 97, thus being
effective in downsizing the resultant apparatus.

The glass substrate 95 is provided with a
minute aperture 96 for determining a width and a
magnitude of the circularly polarized light. The
15 aperture 96 has an important functional effect on
weighting of optical computing. Further, wavelengths
of the pump beam and the probe beam are locked.

Figure 11 shows a high-order gradiometer
constituted by disposing a plurality of polarizing
20 elements, which have polarization angles different by
90 degrees from each other, on a substrate in an array.
By this constitution, a plurality of circularly
polarized lights different in rotational direction can
be disposed at close positions, so that an effect such
25 that gradient information can be detected at the close
positions achieved.
(Embodiment 8)

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Figure 12 is a schematic view for illustrating
Embodiment 8.

In Embodiment 1, the atomic magnetometer
(particularly of SERF (spin-exchange relaxation free)
type) using the probe beam and the pump beam is
described. In this embodiment, an atomic magnetometer
using only the probe beam is employed.

That is, Embodiment 8 is the same as
Embodiment 1 except that the atomic magnetometer is
operated only by the probe beam and that the probe
beam and a direction of a measurement magnetic field
are parallel to each other. By the function of the
half-wave plate 23, a difference between magnetic
field intensities at two measurement positions can be
detected as a difference in polarization rotation
angle. However, in this embodiment, the difference in
detected magnetic field intensity is a difference in
magnetic field intensity in x-axis direction
(Bx2 - Bx1). The atomic magnetometer in which the
probe beam and the magnetic field direction are
parallel to each other and the pump beam is not
employed is, e.g., described in detail in Phys. Rev.
A47, 1220-1226 (1993).

That is, it is understood that the present
invention is not limited to the atomic magnetometer
using both of the probe beam and the pump beam. The
present invention is also applicable to other atomic

·magnetometers including an atomic magnetometer of
FM-NMOR (frequency-modulated nonlinear magneto-optical
rotation)-type as described in Phys. Rev. A73, 053404
(2006).

5   (Embodiment 9)

Figure 13 is a schematic view for illustrating
a characterizing portion of Embodiment 9.

Embodiment 9 is the same as Embodiments 1 and
8 except that the medium providing the polarization

10   rotation angles $\varphi 1$ and $\varphi 2$ is changed from the alkali
metal vapor or the rare gas to a medium such as glass
which achieves the linear Faraday effect in a narrow
sense. In this embodiment, by the function of the
half-wave plate 23 a difference between magnetic field

15   intensities at two measurement positions can be
detected as a difference in polarization rotation
angle.

[INDUSTRIAL APPLICABILITY]

20   As described hereinabove, the present
invention is not limited to the atomic magnetometer
but is also applicable to any magnetometer for measure
a magnetic field intensity as a magnitude of a
polarization rotation angle of a probe beam.

25   While the invention has been described with
reference to the structures disclosed herein, it is
not confined to the details set forth and this

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application is intended to cover such modifications or changes as may come within the purpose of the improvements or the scope of the following claims.

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CLAIMS

1.   An atomic magnetometer comprising:

a light source for a probe beam; and

5   a medium in which the probe beam is to be

propageted,

wherein said medium is a substance which

changes a polarization rotation angle of the probe

beam depending on a magnetic field intensity at a

10   first measurement position and a magnetic field

intensity at a second measurement position different

from the first measurement position, and

wherein said atomic magnetometer directly

measures a difference between the magnetic field

15   intensity at the first measurement position and the

magnetic field intensity at the second measurement

position as a difference in polarization rotation

angle, along a propagation path of the probe beam.

20   2.   A magnetometer according to Claim 1, wherein

said atomic magnetometer comprises:

a cell having a hollow portion;

an atomic group contained in the hollow

portion of said cell to constitute said medium;

25   a pump beam light source for irradiating said

cell with circularly polarized light to polarize a

spin of a plurality of atoms constituting said atomic

group;

said light source, for the probe beam, for
irradiating said cell with linearly polarized light as
the probe beam; and

5   a detector for detecting information on a
polarization rotation angle of the linearly polarized
light,

wherein an irradiation direction of the
circularly polarized light as a pump beam for the
10 atomic group in the cell and an irradiation direction
of the probe beam intersect with each other at the
first measurement position, and an irradiation
direction of the circularly polarized light as a pump
beam for the atomic group in the cell and an
15 irradiation direction of the probe beam having passed
through the first measurement position intersect with
each other at the second measurement position, and

wherein said atomic magnetometer is configured
to perform subtraction between the polarization
20 rotation angle of the probe beam on the basis of the
magnetic field intensity at the first measurement
position and the polarization rotation angle of the
probe beam on the basis of the magnetic field
intensity at the second measurement position.

25

3.   A magnetometer according to Claim 2, wherein
the first measurement position and the second

measurement position are located in a first cell and a
second cell, respectively, and a half-wave plate
configured to pass the probe beam therethrough is
provided between the first cell and the second cell.

5

    4.   A magnetometer according to Claim 2, wherein
the first measurement position and the second
measurement position are located in the cell, and
optical path turning means for passing the probe beam,
10 having passed through the first measurement position,
through the second measurement position with an
opposite traveling direction is provided.

    5.   A magnetometer according to Claim 2, wherein
15 the first measurement position and the second
measurement position are located in the cell, and
        wherein both of the circularly polarized light
for irradiation at the first measurement position and
the circularly polarized light for irradiation at the
20 second measurement position are either one of
right-hand circularly polarized light and left-hand
circularly polarized light, and the circularly
polarized light for irradiation at the first
measurement position and the circularly polarized
25 light for irradiation at the second measurement
position have traveling directions opposite from each
other.

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6.   A magnetometer according to Claim 2, wherein the first measurement position and the second measurement position are located in the cell, and

wherein the circularly polarized light for

5   irradiation at the first measurement position and the circularly polarized light for irradiation at the second measurement position have helicity opposite from each other and have the same traveling direction.

10   7.   A magnetometer according to Claim 2, wherein said atomic magnetometer is configured to have another measurement position which is different from the first measurement position and the second measurement position which are located in the same cell.

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8.   A magnetometer according to Claim 2, wherein said atomic magnetometer is configured to pass laser light from said pump beam light source through a member including a polarization element for equalizing

20   a light intensity of right-hand circularly polarized light with a light intensity of left-hand circularly polarized light and then to pass circularly polarized light through the cell.

25   9.   A magnetic sensing method for measuring a polarization rotation angle of a probe beam by irradiating an atomic group contained in a hollow

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portion of a cell with a pump beam to uniformize

directions of spin of atoms constituting the atomic

group and then by irradiating the spin-polarized

atomic group of the atoms with linearly polarized

5   light as the probe beam, said magnetic sensing method

comprising:

introducing the probe beam having a plane of

polarization rotated by a magnetic field intensity at

a first measurement position to a second measurement

10   position different from the first measurement position

so as to permit subtraction of the polarization

rotation angle of the probe beam; and

obtaining information on a difference between

a magnetic field intensity at the first measurement

15   position and a magnetic field intensity at the second

measurement position by measuring the polarization

rotation angle of the probe beam having passed through

the second measurement position.

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| ROTATE PLANE OF POLARIZED PROBE BEAM BY MAGNETIC FIELD STRENGTH AT 1ST MEASUREMENT POSITION | S1 |

| GUIDE PROBE BEAM TO 2ND MEASUREMENT POSITION AND PERFORM OPTICAL SUBTRACTION OF POLARIZATION ROTATION ANGLE | S2 |

| MEASURE ROTATION ANGLE OF PLANE OF POLARIZED PROBE BEAM PASSED THROUGH 2ND MEASUREMENT POSITION | S3 |

Fig. 1

Fig. 2

2/7
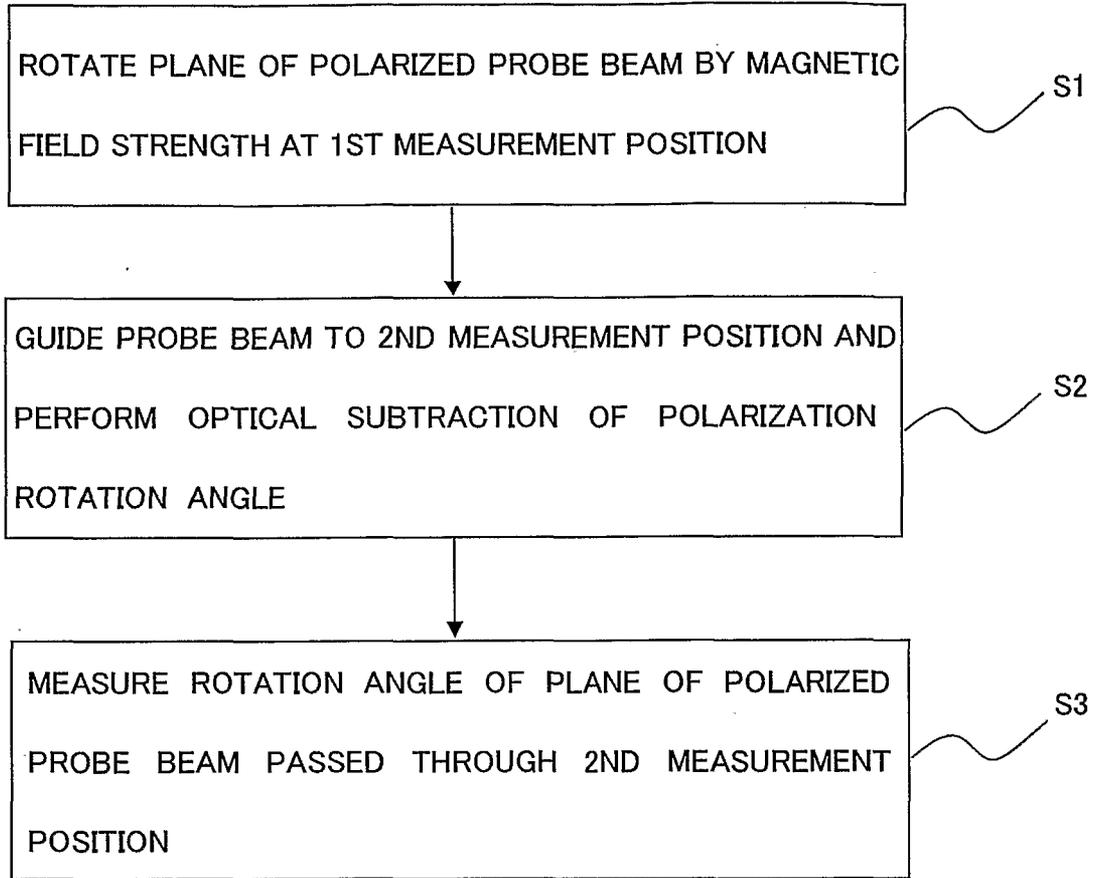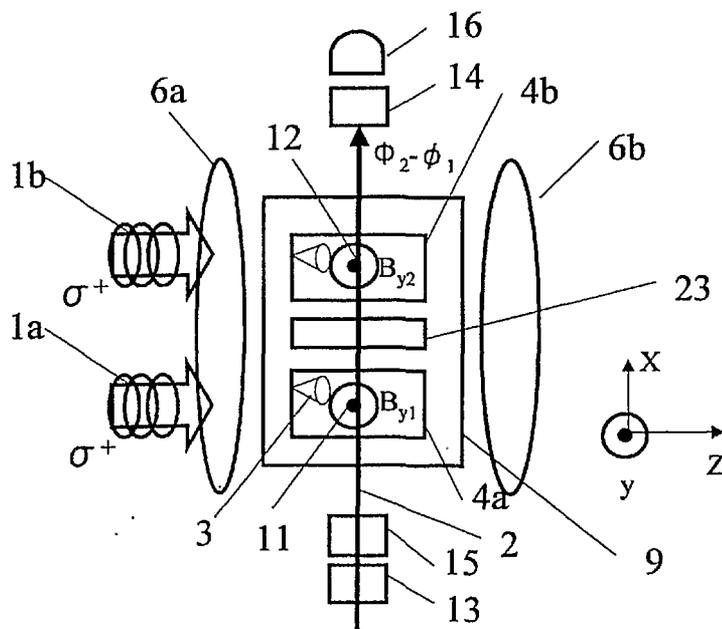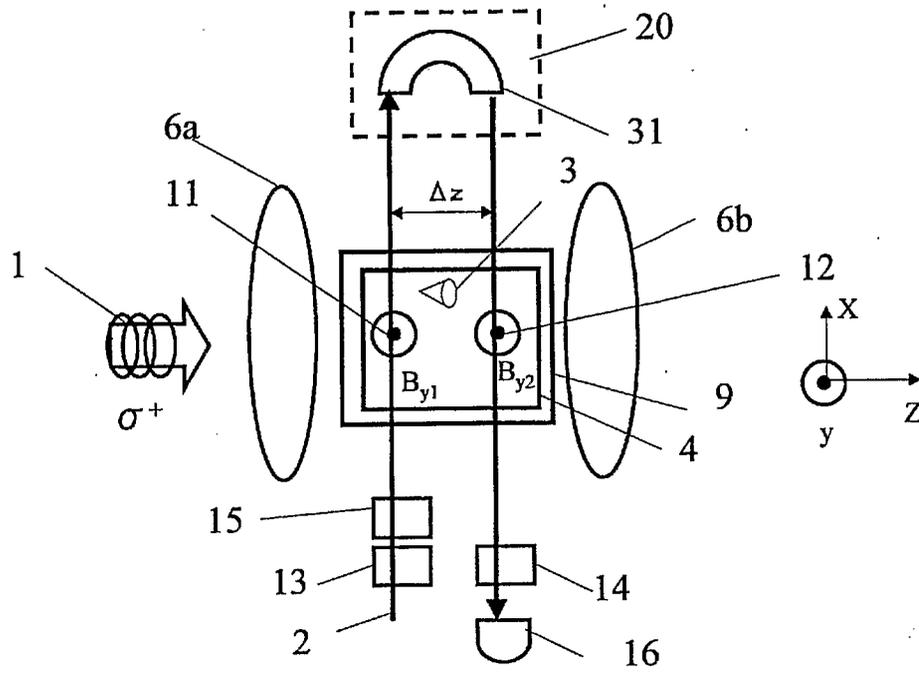
Fig. 3
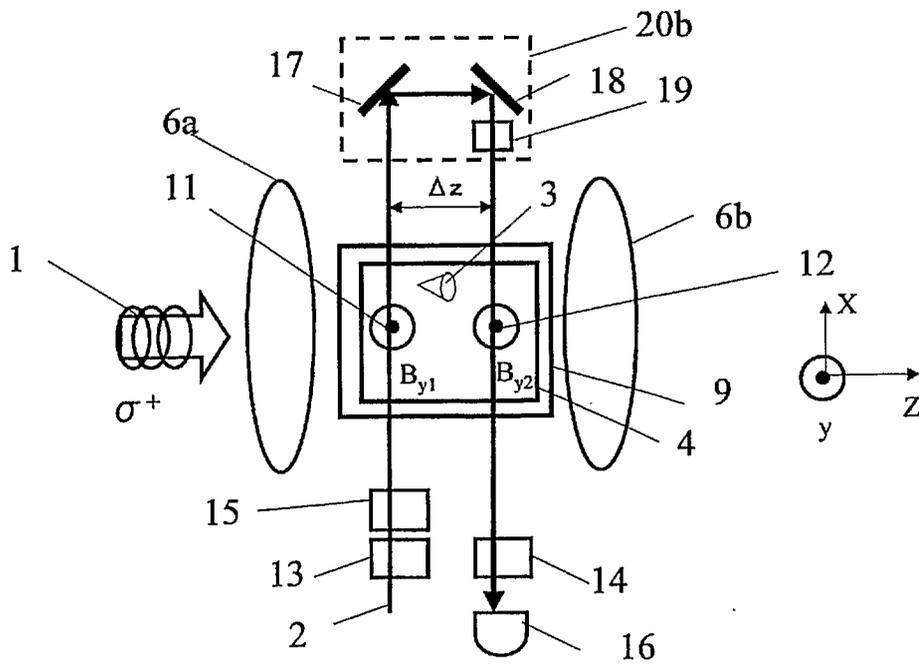
Fig. 4
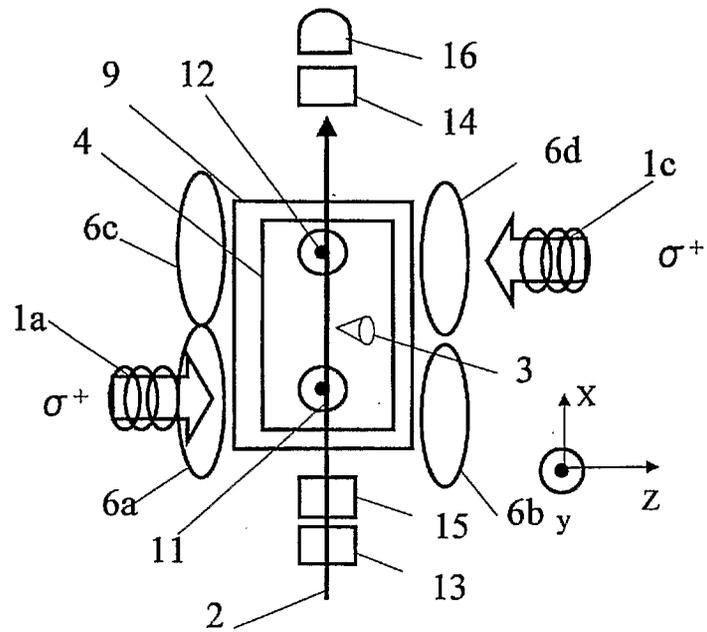
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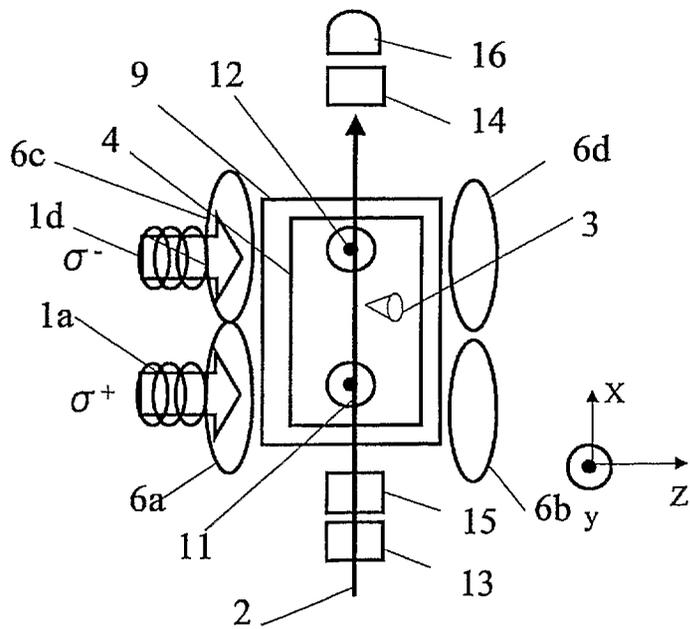
Fig. 6
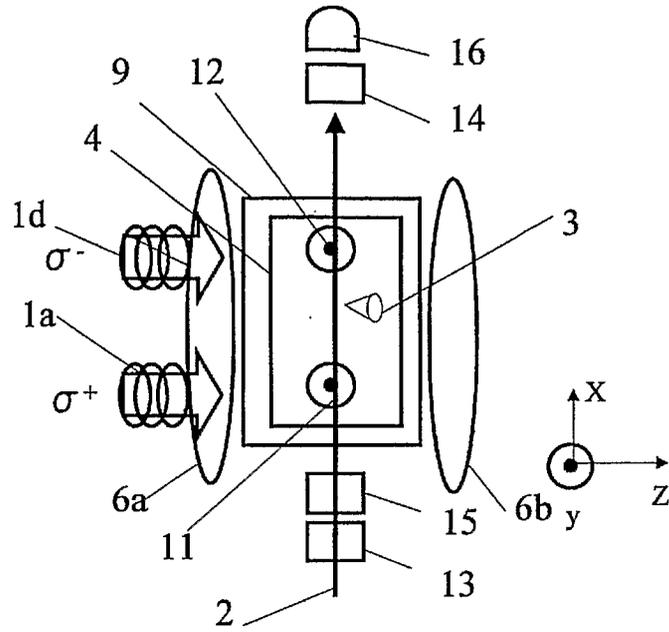
Fig. 7
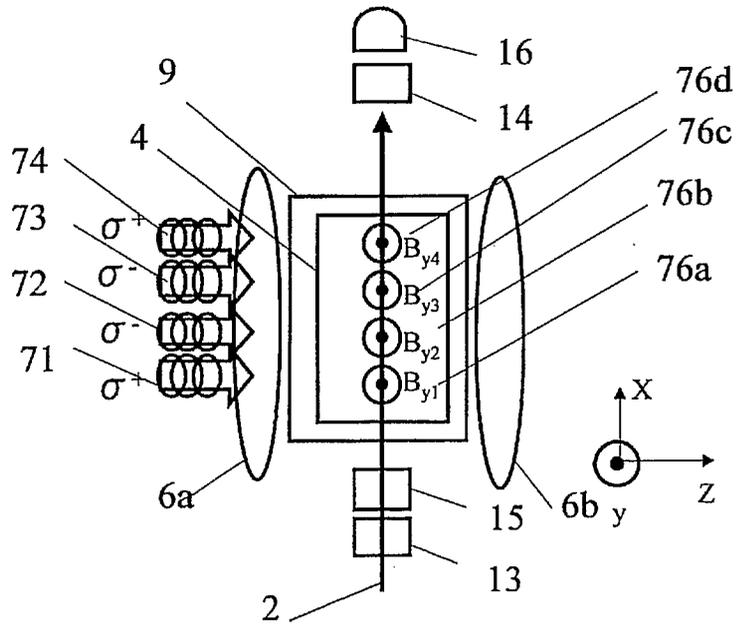
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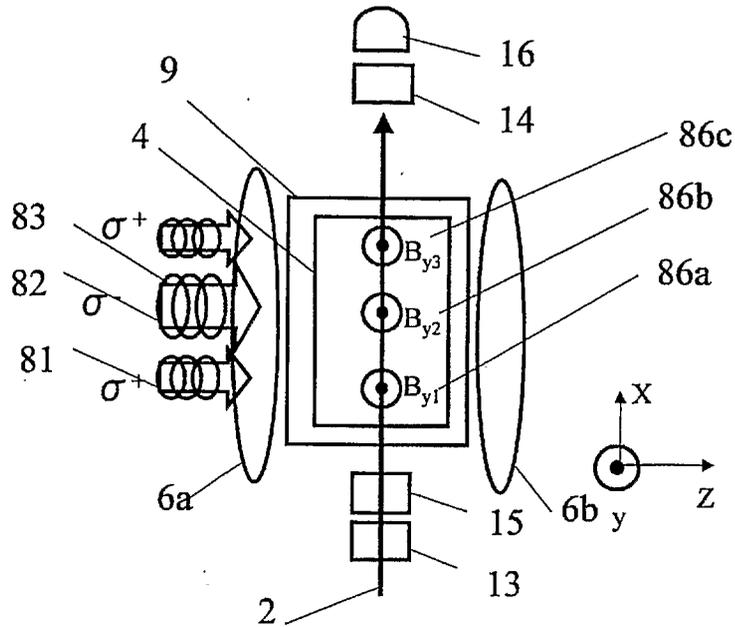
Fig. 9
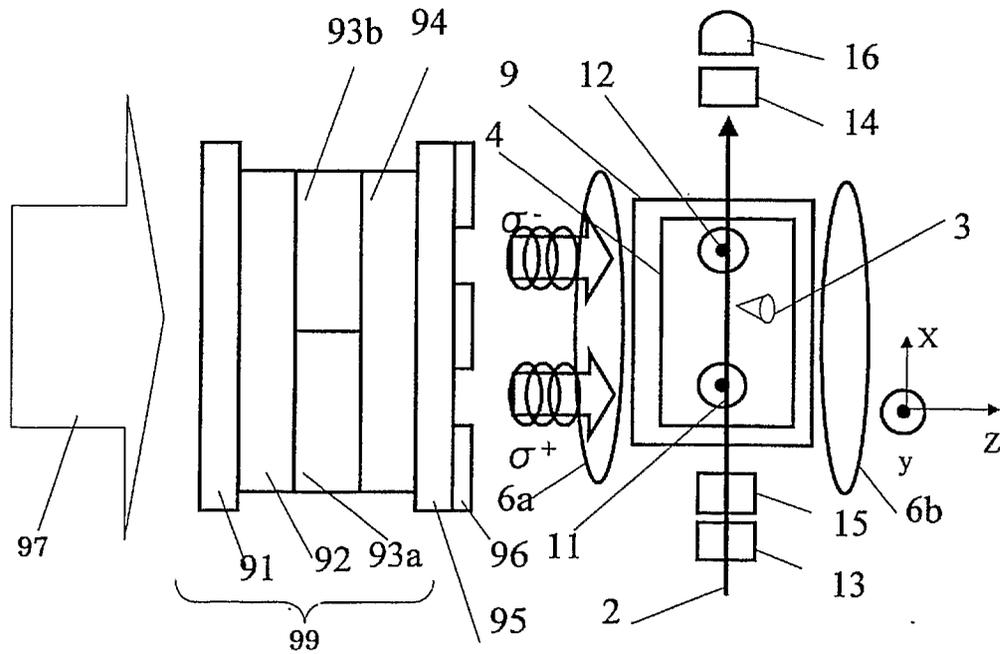
Fig. 10
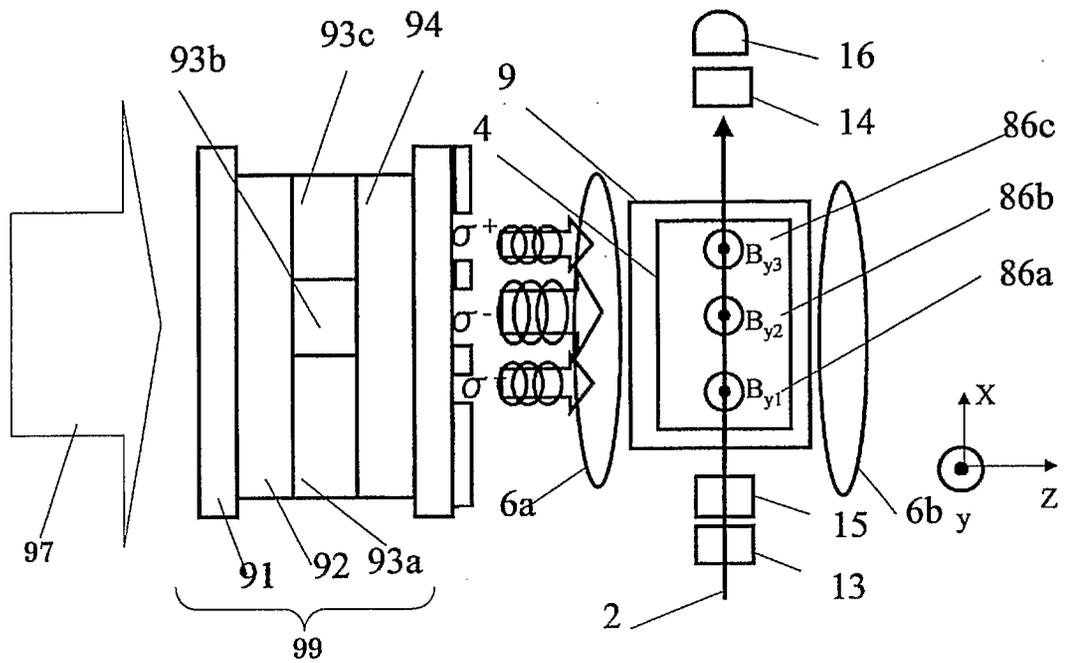
Fig. 11
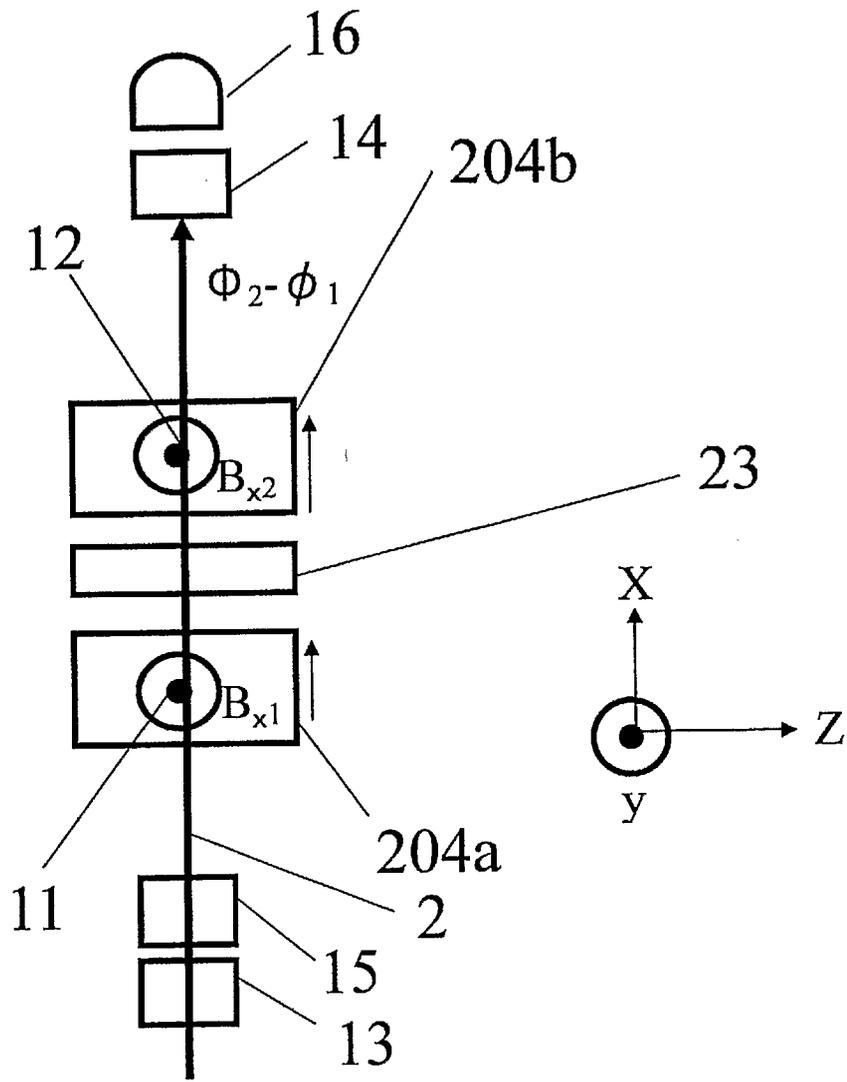
$\Phi_2 - \phi_1$

Fig. 12

Fig. 13

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R33/26   G01R33/022

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01R

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/140799 A1 (ROMALIS MICHAEL [US] ET AL) 22 July 2004 (2004-07-22) cited in the application paragraphs [0084], [0085], [0098], [0100], [0104]; figure 6	1,2,7,8
X	EP 0 130 901 A (THOMSON CSF [FR]) 9 January 1985 (1985-01-09) page 3, lines 11-25 page 5, lines 20-29 page 6, lines 10-31; figure 2	1,2,7,8
A	US 3 863 144 A (SIMPSON JAMES H ET AL) 28 January 1975 (1975-01-28) column 2, line 52 - column 3, line 19	1,9

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

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 April 2009	07/05/2009

| Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016 | Authorized officer Navas Montero, E |

C(Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	HODBY E ET AL: "Differential atomic magnetometry based on a diverging laser beam" APPLIED PHYSICS LETTERS, AIP, AMERICAN INSTITUTE OF PHYSICS, MELVILLE, NY, US, vol. 91, no. 1, 3 July 2007 (2007-07-03), pages 11109-1-11109-3, XP012098925 ISSN: 0003-6951 page -1, right-hand column, lines 7-12,29-35; figure 3	1,9

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

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