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Chiang et al.

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(54) **MAGNETIC FIELD MEASURING METHOD, MAGNETIC FIELD MEASURING SYSTEM AND MAGNETIC FIELD MEASURING APPARATUS**

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(52) **U.S. Cl.**
CPC ***G01R 33/032*** (2013.01); ***G01R 33/0213*** (2013.01)

(58) **Field of Classification Search**
CPC G01R 33/032; G01R 33/0213
See application file for complete search history.

(56) **References Cited**

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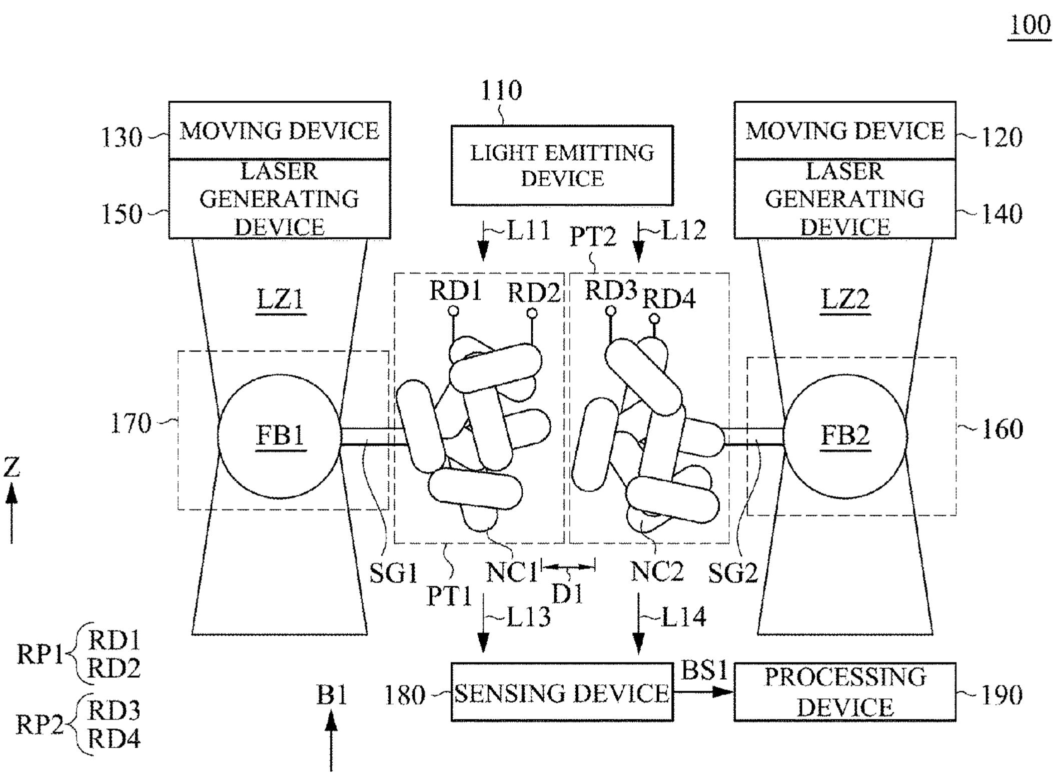
(57) **ABSTRACT**

A magnetic field measuring method includes: applying a magnetic field to a first particle and a second particle; generating a first output light by the first particle according to the magnetic field and a first coupling strength between the first particle and the second particle; and calculating a strength of the magnetic field according to a strength of the first output light. A magnetic field measuring system and a magnetic field measuring apparatus are also disclosed herein.

19 Claims, 4 Drawing Sheets



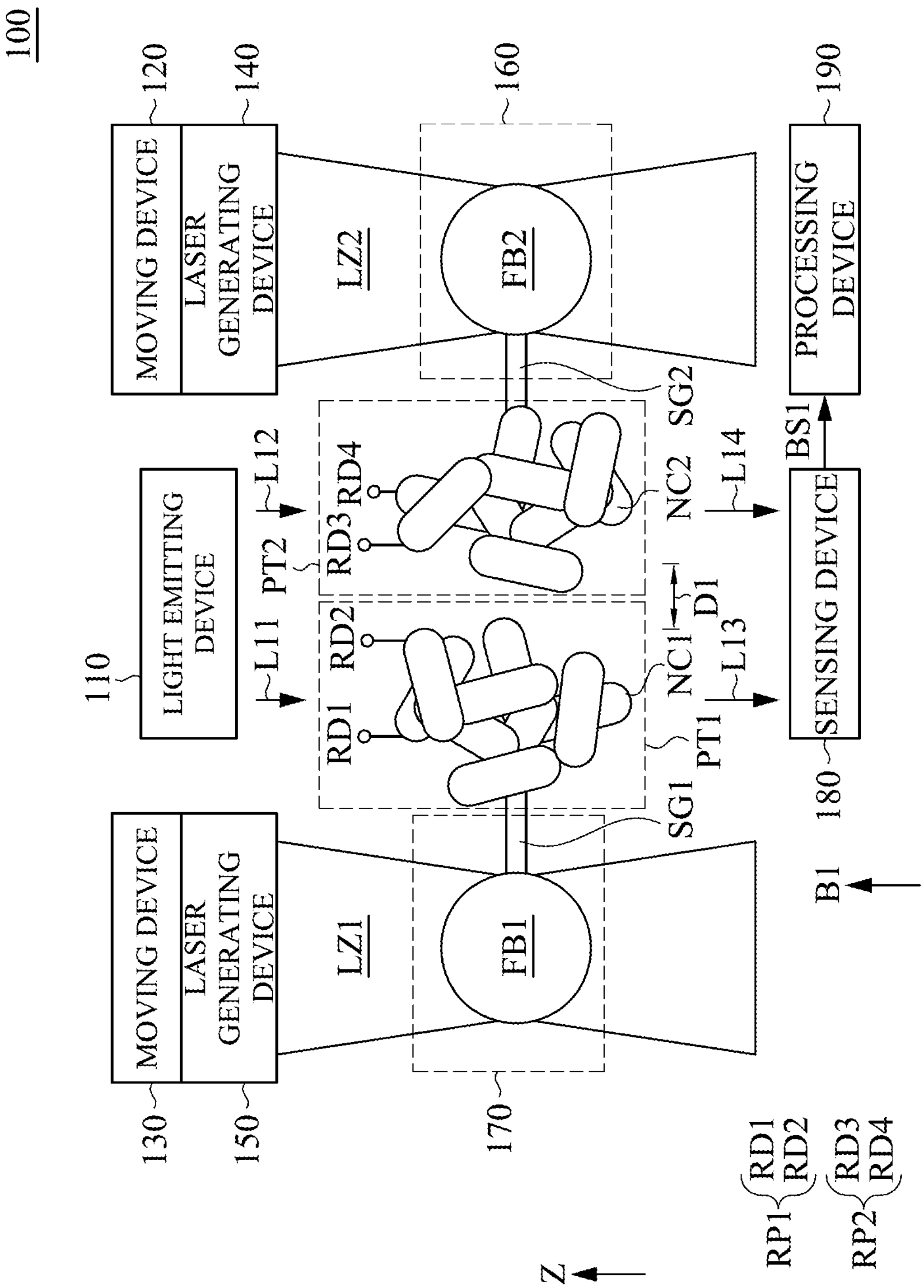

100
110
LIGHT EMITTING DEVICE
120
MOVING DEVICE
140
LASER GENERATING DEVICE
130
MOVING DEVICE
150
LASER GENERATING DEVICE
160
170
LZ1
LZ2
FB1
FB2
SG1
SG2
RD1
RD2
RD3
RD4
PT1
PT2
NC1
NC2
L11
L12
L13
L14
D1
180
SENSING DEVICE
190
PROCESSING DEVICE
BS1
B1
Z
RP1
RD1
RD2
RP2
RD3
RD4

FIG. 1

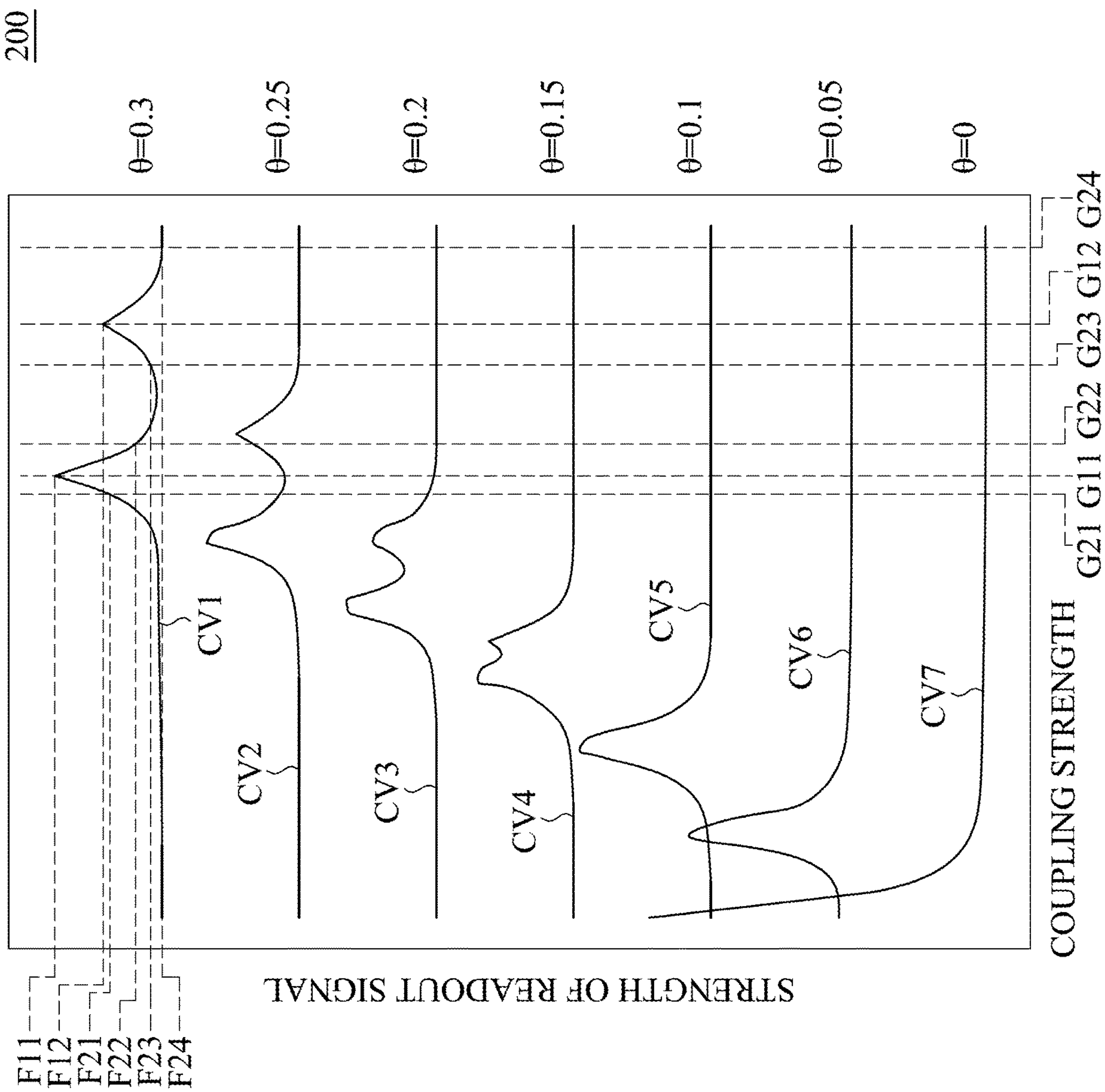

200
θ=0.3
θ=0.25
θ=0.2
θ=0.15
θ=0.1
θ=0.05
θ=0
G21 G11 G22 G23 G12 G24
CV1
CV2
CV3
CV4
CV5
CV6
CV7
COUPLING STRENGTH
STRENGTH OF READOUT SIGNAL
F11
F12
F21
F22
F23
F24

FIG. 2

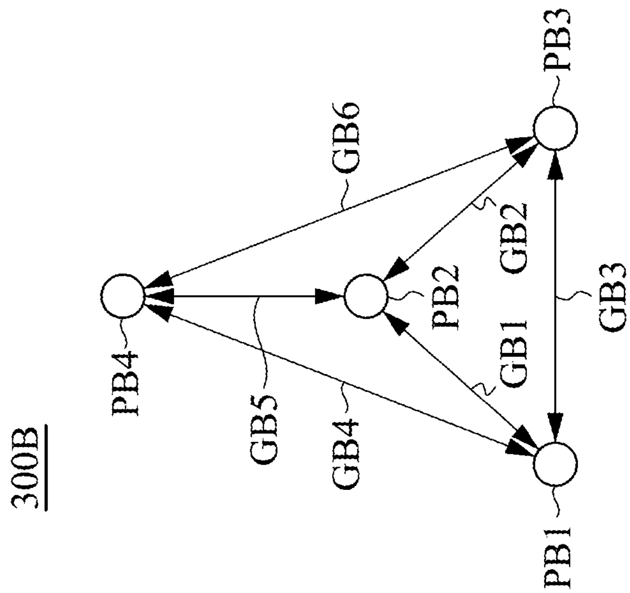

300B
PB1
PB2
PB3
PB4
GB1
GB2
GB3
GB4
GB5
GB6

FIG. 3B

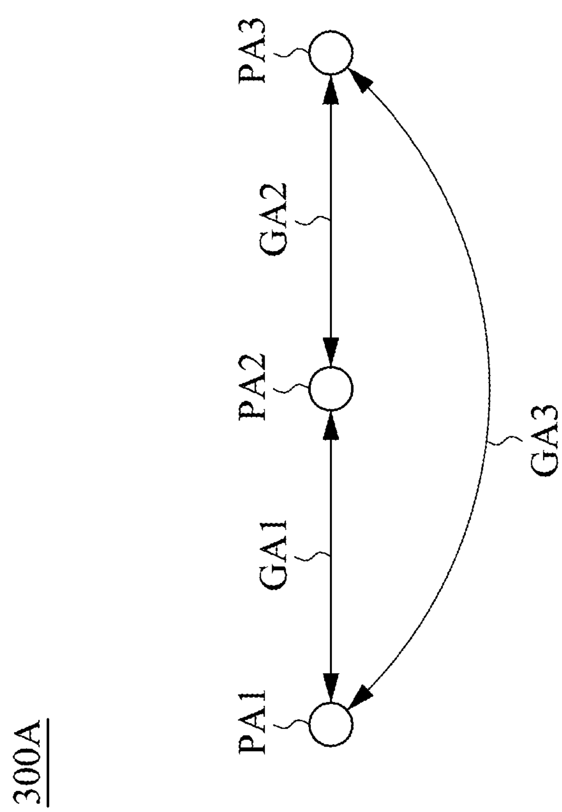

300A
PA1
PA2
PA3
GA1
GA2
GA3

FIG. 3A

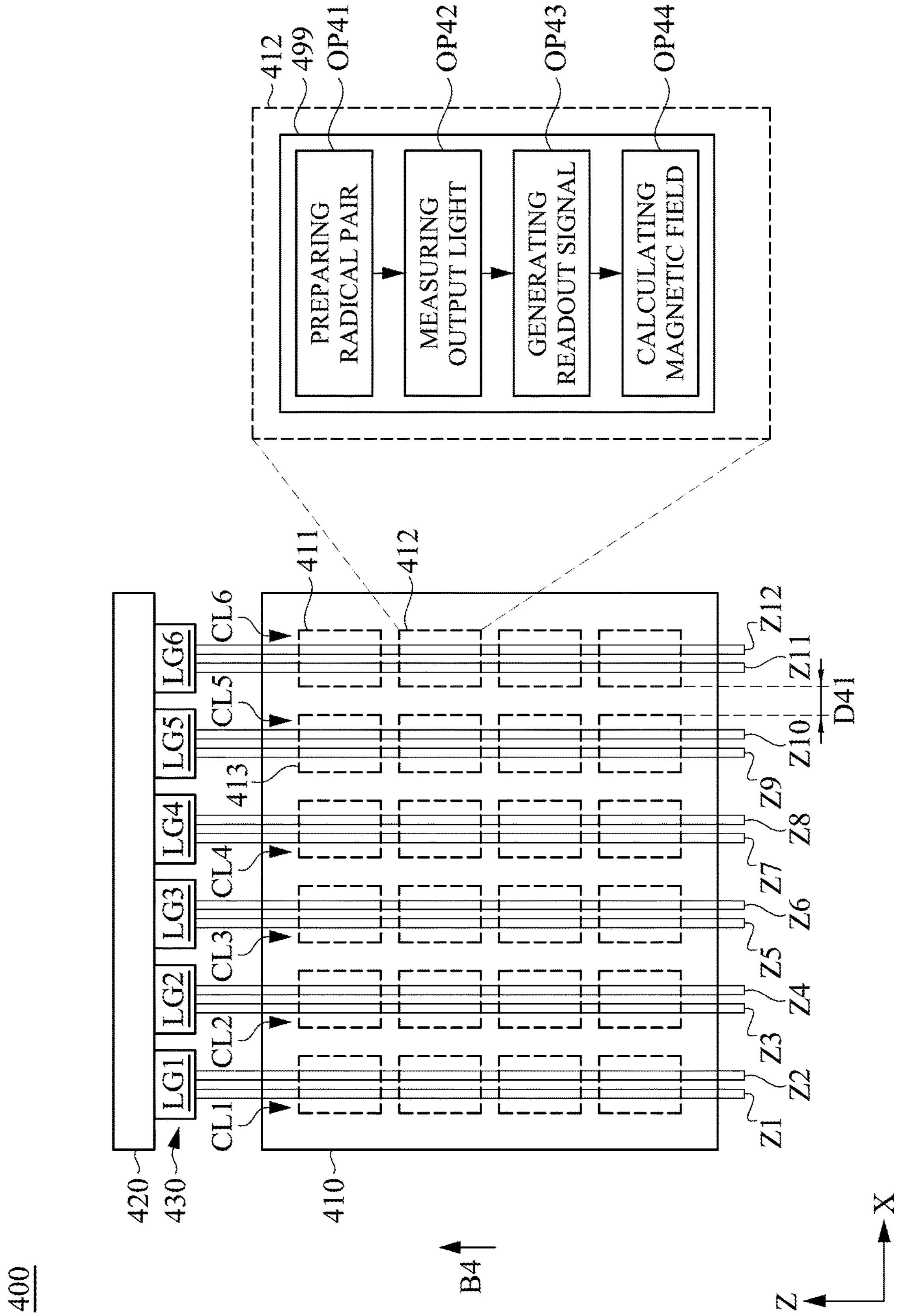

400
B4
Z
X
420
430
410
LG1
LG2
LG3
LG4
LG5
LG6
CL1
CL2
CL3
CL4
CL5
CL6
411
412
413
Z1
Z2
Z3
Z4
Z5
Z6
Z7
Z8
Z9
Z10
Z11
Z12
D41
412
499
OP41
OP42
OP43
OP44
PREPARING RADICAL PAIR
MEASURING OUTPUT LIGHT
GENERATING READOUT SIGNAL
CALCULATING MAGNETIC FIELD

FIG. 4

MAGNETIC FIELD MEASURING METHOD, MAGNETIC FIELD MEASURING SYSTEM AND MAGNETIC FIELD MEASURING APPARATUS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to and the benefit of TW Application Number 111146198, filed Dec. 1, 2022, which claims priority to and the benefit of U.S. Provisional Application No. 63/268,313, filed Feb. 21, 2022, entitled "Flexible magnetic sensing method utilizing radical pair system", which is incorporated herein by reference in its entirety for all purposes.

BACKGROUND

Technical Field

The present disclosure relates to a technology of magnetic field measurements. More particularly, the present disclosure relates to a magnetic field measuring method, a magnetic field measuring system and a magnetic field measuring apparatus.

Description of Related Art

When small cells or devices are observed, measurements for weak magnetic field are required. However, measuring devices for measuring weak magnetic field have various disadvantages, such as need to be operated under very low temperature environments, or the space resolution is not able to be adjusted. Thus, techniques associated with overcoming disadvantages described above are important issues in the field.

SUMMARY

The present disclosure provides a magnetic field measuring method. The magnetic field measuring method includes: applying a magnetic field to a first particle and a second particle; generating a first output light by the first particle according to the magnetic field and a first coupling strength between the first particle and the second particle; and calculating a strength of the magnetic field according to a strength of the first output light.

The present disclosure provides a magnetic field measuring system. The magnetic field measuring system includes a first particle, a second particle and a sensing device. The first particle is configured to generate a first output light according to a first coupling strength and a magnetic field. The second particle is configured to be coupled to the first particle with the first coupling strength. The sensing device is configured to generate a readout signal corresponding to a strength of the magnetic field according to a strength of the first output light.

The present disclosure provides a magnetic field measuring apparatus. The magnetic field measuring apparatus includes a first sensing module, a second sensing module, a first laser generating device, a second laser generating device and a moving device. The first sensing module is configured to calculate a first strength of a magnet field surrounding the first sensing module. The second sensing module is configured to calculate a second strength of the magnet field surrounding the second sensing module. The first laser generating device is configured to position the first sensing module. The second laser generating device is configured to position the second sensing module. The moving device is configured to move at least one of the first laser generating device and the second laser generating device, to adjust a distance between the first sensing module and the second sensing module.

It is to be understood that both the foregoing general description and the following detailed description are by examples, and are intended to provide further explanation of the disclosure as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. **1** is a schematic diagram of a magnetic field measuring system illustrated according to one embodiment of the present disclosure.

FIG. **2** is a relationship diagram of signal strength of a readout signal, a coupling strength and an external field, illustrated according to one embodiment of the present disclosure.

FIG. **3**A is a schematic diagram of a magnetic field measuring system illustrated according to one embodiment of the present disclosure.

FIG. **3**B is a schematic diagram of a magnetic field measuring system illustrated according to one embodiment of the present disclosure.

FIG. **4** is a schematic diagram of a magnetic field measuring apparatus illustrated according to one embodiment of the present disclosure.

DETAILED DESCRIPTION

In the present disclosure, when an element is referred to as "connected" or "coupled", it may mean "electrically connected" or "electrically coupled". "Connected" or "coupled" can also be used to indicate that two or more components operate or interact with each other. In addition, although the terms "first", "second", and the like are used in the present disclosure to describe different elements, the terms are used only to distinguish the elements or operations described in the same technical terms. The use of the term is not intended to be a limitation of the present disclosure.

Unless otherwise defined, all terms (including technical and scientific terms) used in the present disclosure have the same meaning as commonly understood by the ordinary skilled person to which the concept of the present invention belongs. It will be further understood that terms (such as those defined in commonly used dictionaries) should be interpreted as having a meaning consistent with its meaning in the related technology and/or the context of this specification and not it should be interpreted in an idealized or overly formal sense, unless it is clearly defined as such in this article.

The terms used in the present disclosure are only used for the purpose of describing specific embodiments and are not intended to limit the embodiments. As used in the present disclosure, the singular forms "a", "one" and "the" are also intended to include plural forms, unless the context clearly indicates otherwise. It will be further understood that when used in this specification, the terms "comprises (comprising)" and/or "includes (including)" designate the existence of stated features, steps, operations, elements and/or components, but the existence or addition of one or more other features, steps, operations, elements, components, and/or groups thereof are not excluded.

Hereinafter multiple embodiments of the present disclosure will be disclosed with schema, as clearly stated, the details in many practices it will be explained in the following description. It should be appreciated, however, that the details in these practices is not applied to limit the present disclosure. Also, it is to say, in some embodiments of the present disclosure, the details in these practices are non-essential. In addition, for the sake of simplifying schema, some known usual structures and element in the drawings by a manner of simply illustrating for it.

FIG. **1** is a schematic diagram of a magnetic field measuring system **100** illustrated according to one embodiment of the present disclosure. In some embodiments, the magnetic field measuring system **100** is configured to measure a magnetic field B**1** applied to the magnetic field measuring system **100**.

In some embodiments, the magnetic field measuring system **100** may be a quantum measuring system, which includes particles PT**1**, PT**2**, a light emitting device **110**, moving devices **120**, **130**, laser generating devices **140**, **150**, a fixing device **160**, **170**, a sensing device **180** and a processing device **190**.

As illustratively shown in FIG. **1**, the light emitting device **110** is configured to emit input lights L**11** and L**12** to the particles PT**1**, PT**2**. The particle PT**1** is configured to generate an output light L**13** according to the input light L**11**. The particle PT**2** is configured to generate an output light L**14** according to the input light L**12**. In some embodiments, wavelengths of the input lights L**11** and L**12** are approximately equal to 473 nanometers, and wavelengths of the output lights L**13** and L**14** are approximately equal to 550 nanometers. In various embodiments, the input lights L**11** and L**12** and the output lights L**13** and L**14** may have various wavelengths.

As illustratively shown in FIG. **1**, the sensing device **180** is configured to receive at least one of the output lights L**13** and L**14**, and configured to generate a readout signal BS**1** according to at least one of the output lights L**13** and L**14**. The processing device **190** performs calculations according to the readout signal BS**1**, to obtain a strength of the magnetic field B**1**.

In some embodiments, the particle PT**1** includes a nucleus NC**1** and a radical pair RP**1**, and the particle PT**2** includes a nucleus NC**2** and a radical pair RP**2**. The radical pair RP**1** includes radicals RD**1** and RD**2**, and the radical pair RP**2** includes radicals RD**3** and RD**4**. In some embodiments, the nucleuses NC**1** and NC**2** may be implemented by proteins or synthesized molecules. The radical pairs RP**1** and RP**2** may be implemented by lone pairs. The radicals RD**1**-RD**4** may be implemented by electrons.

As illustratively shown in FIG. **1**, a distance between the radicals RD**2** and RD**3** is shorter than a distance between the radicals RD**2** and RD**4**, and the distance between the radicals RD**2** and RD**3** is shorter than a distance between the radicals RD**1** and RD**3**. In some embodiments, a coupling strength G**1** between the radicals RD**2** and RD**3** is stronger than each of a coupling strength between the radicals RD**2** and RD**4** and a coupling strength between the radicals RD**1** and RD**3**.

In some embodiments, the magnetic field B**1** is applied to the particles PT**1** and PT**2**. The particle PT**1** is configured to generate the output light L**13** according to the input light L**11**, the magnetic field B**1** and the coupling strength G**1**. The particle PT**2** is configured to generate the output light L**14** according to the input light L**12**, the magnetic field B**1** and the coupling strength G**1**. In some embodiments, a strength of the output light L**13** and a strength of the output light L**14** are related with the coupling strength G**1**.

In some embodiments, a Hamiltonian function H representing energy of the particles PT**1** and PT**2** may be represented by equation (1) as following:

$$H=a\cdot S_{A1}\cdot I_1+\theta(S_{A1}{}^Z+S_{B1}{}^Z)+a\cdot S_{B1}\cdot I_2+\theta(S_{A2}{}^Z+S_{B2}{}^Z)+G1\cdot S_{B1}{}^Z\cdot S_{B2}{}^Z \quad (1).$$

In some embodiments, in the equation (1), the "a" represents a coefficient of hyperfine interaction, the S_{A1} corresponds to spin of the radical RD**1**, the I_1 corresponds to spin of the particle PT**1**, the S_{B1} corresponds to spin of the radical RD**2**, the I_2 corresponds to spin of the particle PT**2**, the $S_{A1}{}^Z$ corresponds to a component of the spin of the radical RD**1** on the Z-direction, the $S_{B1}{}^Z$ corresponds to a component of the spin of the radical RD**2** on the Z-direction, the $S_{A2}{}^Z$ corresponds to a component of the spin of the radical RD**4** on the Z-direction, the $S_{B2}{}^Z$ corresponds to a component of the spin of the radical RD**3** on the Z-direction, and the θ corresponds to an external field applied to the particles PT**1** and PT**2**. In some embodiments, the Z-direction is parallel with a direction of the magnetic field B**1**. In some embodiments, a relationship between the external field θ and the magnetic field B**1** may be represented by equation (2) as following, in which the γ_e is a constant:

$$B1=\theta/\gamma_e \quad (2).$$

In some embodiments, corresponding to the Hamiltonian function H, the particles PT**1** and PT**2** have eigenstates |m> and |n>. It is noted that the m and n are positive integers. Energy corresponding to the eigenstates |m> and |n>, which are eigenvalues corresponding to the eigenstates |m> and |n>, include information of the external field θ and the coupling strength G**1**. Alternatively stated, the eigenvalues corresponding to the eigenstate |m> and |n> may change with respect to the change of the external field θ and/or the coupling strength G**1**.

In some embodiments, each of the strength of the output light L**13** and the strength of the output light L**14** may be represented by the function Φ(θ) shown in equation (3) as following. In some embodiments, the function Φ(θ) corresponds to a signal strength of the readout signal BS**1**, such as a current level or a voltage level of the readout signal BS**1**. In some embodiments, the signal strength of the readout signal BS**1** corresponds to at least one of the strength of the output light L**13** and the strength of the output light L**14**.

$$\Phi(\theta)=\frac{1}{M}\sum_{m=1}^{4M}\sum_{n=1}^{4M}\hat{P}_{mn}\cdot\rho_{mn}\cdot f(\omega_{mn}). \quad (3)$$

In some embodiments, the ρ_{mn} in the equation (3) corresponds to a density function. The M is a positive integer. The ω_{mn} corresponds an energy difference between an energy level of the eigenstate |m> and an energy level of the eigenstate |n>. The $\hat{P}_{mn}$ may be represented by equation (4) as following. The $f(\omega_{mn})$ may be represented by equation (5) as following.

$$\hat{P}_{mn}=\langle m|\hat{P}|n\rangle. \quad (4)$$

-continued

$$f(\omega_{mn}) = \frac{k^2}{k^2 + \omega_{mn}^2}. \tag{5}$$

In some embodiments, the $\hat{P}$ in the equation (4) corresponds to a projection operator. The k in the equation (5) is a constant number.

As the equation (1) to the equation (5) described above, the function $\Phi(\theta)$ changes with respect to the change of the external field θ and the coupling strength **G1**. According to calculations with the equation (1) to the equation (5), coupling strength values **G11**-**G12** shown in following equations (6)-(7) are derived. The function $\Phi(\theta)$ has local peak values when the coupling strength **G1** has the coupling strength values **G11**-**G12**.

$$G11 = \frac{1}{4}(\theta + (1 - \Omega)). \tag{6}$$

$$G12 = \frac{1}{4}(\theta - (1 - \Omega)). \tag{7}$$

In some embodiments, the function Ω in the equations (6)-(7) is a function of the external field θ. Under a condition that the coupling strength values **G11**-**G12** are known the strength of the external field θ may be derived by equation (8) as following.

$$\theta = 2 \cdot (G11 + G12) \tag{8}$$

In some embodiments, the processing device **190** is configured to perform the calculations of the equations (1)-(8). In various embodiments, the equations (1)-(8) have various forms.

As illustratively shown in FIG. **1**, the fixing device **160** is configured to fix the particle **PT2**, and the fixing device **170** is configured to fix the particle **PT1**. The laser generating device **150** is configured to generate a laser **LZ1**, and is configured to position the fixing device **170** in the space by the laser **LZ1**. The laser generating device **140** is configured to generate a laser **LZ2**, and is configured to position the fixing device **160** in the space by the laser **LZ2**.

In some embodiments, the fixing device **170** includes a fixing body **FB1** and a line segment **SG1**, and the fixing device **160** includes a fixing body **FB2** and a line segment **SG2**. As illustratively shown in FIG. **1**, the fixing body **FB1** is configured to be fixed in the space by the laser **LZ1**, and the line segment **SG1** is configured to connect the fixing body **FB1** and the particle **PT1**. The fixing body **FB2** is configured to be fixed in the space by the laser **LZ2**, and the line segment **SG2** is configured to connect the fixing body **FB2** and the particle **PT2**. In some embodiments, the fixing bodies **FB1** and **FB2** are implemented by plastic particles, and the line segments **SG1** and **SG2** are implemented by proteins. In various embodiments, the fixing bodies **FB1** and **FB2** and the line segments **SG1** and **SG2** may be implemented by various shapes and materials.

In some embodiments, the moving device **130** is configured to move a position of the laser generating device **150**, such that a position of the laser **LZ1** is changed, to adjust positions of the fixing device **170** and the particle **PT1**. The moving device **120** is configured to move a position of the laser generating device **140**, such that a position of the laser **LZ2** is changed, to adjust positions of the fixing device **160** and the particle **PT2**. As illustratively shown in FIG. **1**, a distance **D1** perpendicular with the Z direction is between the particles **PT1** and **PT2**. The moving device **120** and **130** are configured to adjust the distance **D1** by adjusting the positions of the particles **PT1** and **PT2**.

In some embodiments, when the distance **D1** is increased, the coupling strength **G1** is decreased. When the distance **D1** is decreased, the coupling strength **G1** is increased. In some embodiments, the moving devices **120** and **130** are configured to adjust the coupling strength **G1** by adjusting the distance **D1**, to change the signal strength of the readout signal **BS1**. Details associated with adjusting the coupling strength **G1** are further described below with the embodiments associated with FIG. **2**.

FIG. **2** is a relationship diagram **200** of a signal strength of the readout signal **BS1**, the coupling strength **G1** and the external field θ, illustrated according to one embodiment of the present disclosure. As illustratively shown in FIG. **2**, a horizontal axis of the relationship diagram **200** corresponds to the coupling strength **G1**, and a vertical axis of the relationship diagram **200** corresponds to the signal strength of the readout signal **BS1**. The relationship diagram **200** includes curves **CV1**-**CV7**.

In some embodiments, the curves **CV1**-**CV7** correspond to different strength of the external field θ. In the embodiment shown in FIG. **2**, the curves **CV1**-**CV7** to the external field θ having strengths of 0.3, 0.25, 0.2, 0.15, 0.1, 0.05 and 0, respectively.

Referring to FIG. **1** and FIG. **2**, when the external field θ (that is, the magnetic field **B1**) is applied to the particles **PT1** and **PT2**, the moving devices **120** and **130** are configured to change the distance **D1** to derive a corresponding one of the curves **CV1**-**CV7**, and derive corresponding local peak values. After the local peak values are derived, the strength of the external field θ may be calculated according to the local peak values.

An example is made following with the curve **CV1** with the strength of the external field θ being 0.3. When the moving device **130** moves the particle **PT1** toward the particle **PT2** and/or when the moving device **120** moves the particle **PT2** toward the particle **PT1**, the distance **D1** is decreased gradually, such that the coupling strength **G1** is increased gradually.

During the operations described above, the coupling strength **G1** has the coupling strength values **G21**, **G11**, **G22**, **G23**, **G12** and **G24** in order. The sensing device **180** receives at least one of the output lights **L13** and **L14**, to derive the signal strength values of the readout signal **BS1** corresponding to the coupling strength values **G21**, **G11**, **G22**, **G23**, **G12** and **G24** in order.

As illustratively shown in FIG. **2**, when the coupling strength **G1** has the coupling strength value **G21**, the readout signal **BS1** has a signal strength value **F21**. When the coupling strength **G1** has the coupling strength value **G11**, the readout signal **BS1** has a signal strength value **F11**. When the coupling strength **G1** has the coupling strength value **G22**, the readout signal **BS1** has a signal strength value **F22**. When the coupling strength **G1** has the coupling strength value **G23**, the readout signal **BS1** has a signal strength value **F23**. When the coupling strength **G1** has the coupling strength value **G12**, the readout signal **BS1** has a signal strength value **F12**. When the coupling strength **G1** has the coupling strength value **G24**, the readout signal **BS1** has a signal strength value **F24**.

As illustratively shown in FIG. **2**, the signal strength value **F11** is larger than the signal strength values **F21** and **F22**, and the signal strength value **F12** is larger than the signal strength values **F23** and **F24**. Accordingly, the signal strength values **F11** and **F12** are the local peak values of the curve **CV1**. As a result, the processing device **190** shown in

FIG. **1** may calculate the strength of the external field θ being 0.3 according to the equation (8) and the coupling strength values G**11**, G**12** corresponding to the signal strength values F**11** and F**12**.

For another example, when the moving device **130** moves the particle PT1 away from the particle PT2 and/or when the moving device **120** moves the particle PT**2** away from the particle PT1, the distance D1 is increased gradually, such that the coupling strength G1 is decreased gradually.

During the operations described above, the coupling strength G1 has the coupling strength values G**24**, G**12**, G**23**, G**22**, G**11** and G**21** in order. The sensing device **180** receives at least one of the output lights L**13** and L**14**, to derive the signal strength values of the readout signal BS1 corresponding to the coupling strength values G**24**, G**12**, G**23**, G**22**, G**11** and G**21** in order.

In various embodiments, the sensing device **180**, the moving device **120** and **130** are configured to perform similar operations to derive the local peak values of the curves CV**2**-CV**7**, and calculate the strength of the external field θ according to the corresponding local peak values.

In some approaches, operating conditions with extremely low temperature is required for measuring device performing fine measurement to magnetic fields, or the space resolution of the measuring device is limited by the manufacturing process and cannot be changed easily.

Compare to above approaches, in embodiments of present disclosure, the sensing device **180** generates the readout signal BS**1** corresponding to the magnetic field B**1** according to the coupling strength G1 between the particle PT**1** having the radical pair RP**1** and the particle PT**2** having the radical pair RP**2**. The magnetic field measuring system **100** does not need a low temperature circumstance to perform fine measurements to the magnetic field B**1**. In some embodiments, a sensitivity of the magnetic field measuring system **100** is approximately equal to $1\mathrm{nT}/\sqrt{\mathrm{Hz}}$, in which nT is nano-Tesla, and Hz is Hertz.

Furthermore, compare to above approaches, in embodiments of present disclosure, the moving devices **120** and **130** may be configured in various ways to have various space resolutions. In some embodiments, space resolutions of the magnetic field measuring system **100** can be smaller than 10 nanometers.

FIG. **3**A is a schematic diagram of a magnetic field measuring system **300**A illustrated according to one embodiment of the present disclosure. In some embodiments, the magnetic field measuring system **300**A includes particles PA**1**-PA3. As illustratively shown in FIG. **3**A, a coupling strength GA**1** is between the particles PA**1** and PA**2**. A coupling strength GA**2** is between the particles PA**3** and PA**2**. A coupling strength GA**3** is between the particles PA**1** and PA**3**. In some embodiments, each of the coupling strengths GA**1**-GA**3** is affected by magnetic fields applied to the particles PA**1**-PA**3**. In some embodiments, the magnetic field measuring system **300**A only performs operations according to a part of the coupling strengths GA**1**-GA**3**. For example, the magnetic field measuring system **300**A may perform operations only according to the coupling strengths GA**1** and GA**2**. In some embodiments, an all to all connection is not required between the particles PA**1**-PA**3**.

Referring to FIG. **1** and FIG. **3**A, the magnetic field measuring system **300**A is an alternative embodiment of the magnetic field measuring system **100**. In some embodiments, configurations of two of the particles PA**1**-PA**3** are similar with the configurations of the particles PT1 and PT2. Therefore, some descriptions are not repeated for brevity.

For example, in some embodiments, the fixing device **170** is configured to fix the particle PA**1**, and the fixing device **160** is configured to fix the particle PA**2**. The light emitting device **110** is configured to emit the input lights L**11** and L**12** to the particles PA**1** and PA**2**, respectively. The particles PA**1** and PA**2** are configured to generate the output lights L**13** and L**14**, respectively, according to the coupling strength GA**1**. The sensing device **180** is configured to generate the readout signal BS**1** corresponding to the magnetic field applied to the particles PA**1** and PA**2** according to the output lights L**13** and L**14**.

In some embodiments, the particles PA**1** and PA**2** are configured to generate the output lights L**13** and L**14** further according to the coupling strengths GA**1**-GA**3**. The sensing device **180** is configured to generate the readout signal BS**1** corresponding to the magnetic field applied to the particles PA1-PA**3** according to the output lights L**13** and L**14**.

In some embodiments, the moving device **130** is configured to adjust a distance between the particles PA**1** and PA**2**, to adjust the coupling strength GA**1**. In some embodiments, the moving device **130** is further configured to adjust a distance between the particles PA**1** and PA3, to adjust the coupling strength GA3.

Similarly, in some embodiments, the moving device **140** is configured to adjust the distance between the particles PA1 and PA2, to adjust the coupling strength GA**1**. In some embodiments, the moving device **140** is further configured to adjust a distance between the particles PA**2** and PA**3**, to adjust the coupling strength GA**2**.

In some embodiments, the magnetic field measuring system **300**A further includes a moving device (not shown in figures) configured to control the particle PA**3**. The moving device controlling the particle PA**3** is configured to adjust a distance between the particles PA1 and PA3, to adjust the coupling strength GA3. The moving device controlling the particle PA**3** is further configured to adjust the distance between the particles PA**2** and PA3, to adjust the coupling strength GA**2**.

FIG. **3**B is a schematic diagram of a magnetic field measuring system **300**B illustrated according to one embodiment of the present disclosure. In some embodiments, the magnetic field measuring system **300**B includes particles PB**1**-PB**4**.

As illustratively shown in FIG. **3**A, a coupling strength GB**1** is between the particles PB**1** and PB**2**. A coupling strength GB**2** is between the particles PB**3** and PB**2**. A coupling strength GB**3** is between the particles PB**1** and PB**3**. A coupling strength GB**4** is between the particles PB**1** and PB**4**. A coupling strength GB**5** is between the particles PB**4** and PB**2**. A coupling strength GB**6** is between the particles PB**4** and PB**3**. In some embodiments, each of the coupling strengths GB**1**-GB**6** is affected by magnetic fields applied to the particles PB**1**-PB**4**. In some embodiments, the magnetic field measuring system **300**B only performs operations according to a part of the coupling strengths GB**1**-GB**6**. For example, the magnetic field measuring system **300**B may performs operations only according to the coupling strengths GB**1**, GB**2** and GB**5**, without performing operations according to the coupling strengths GB**3**, GB**4** and GB**6**. In some embodiments, an all to all connection is not required between the particles PB**1**-PB**4**.

Referring to FIG. **1** and FIG. **3**B, the magnetic field measuring system **300**B is an alternative embodiment of the magnetic field measuring system **100**. In some embodiments, configurations of two of the particles PB**1**-PB**4** are similar with the configurations of the particles PT1 and PT**2**. Therefore, some descriptions are not repeated for brevity.

For example, in some embodiments, the fixing device **170** is configured to fix the particle PB**1**, and the fixing device **160** is configured to fix the particle PB**2**. The light emitting device **110** is configured to emit the input lights L**11** and L**12** to the particles PB**1** and PB**2**, respectively. The particles PB**1** and PB**2** are configured to generate the output lights L**13** and L**14**, respectively, according to the coupling strength GB**1**. The sensing device **180** is configured to generate the readout signal BS**1** corresponding to the magnetic field applied to the particles PB**1** and PB**2** according to the output lights L**13** and L**14**.

In some embodiments, the particles PB**1** and PB**2** are configured to generate the output lights L**13** and L**14** further according to a part or all of the coupling strengths GB**1**-GB**6**. The sensing device **180** is configured to generate the readout signal BS**1** corresponding to the magnetic field applied to the particles PB**1**-PB**4** according to the output lights L**13** and L**14**.

In some embodiments, the moving device **130** is configured to adjust a distance between the particles PB**1** and PB**2**, to adjust the coupling strength GB**1**. The moving device **130** is further configured to adjust a distance between the particles PB**1** and PB**3**, to adjust the coupling strength GB**3**. The moving device **130** is further configured to adjust a distance between the particles PB**1** and PB**4**, to adjust the coupling strength GB**4**.

Similarly, in some embodiments, the moving device **140** is configured to adjust the distance between the particles PB**1** and PB**2**, to adjust the coupling strength GB**1**. The moving device **140** is further configured to adjust a distance between the particles PB**2** and PB**3**, to adjust the coupling strength GB**2**. The moving device **140** is further configured to adjust a distance between the particles PB**2** and PB**4**, to adjust the coupling strength GB**5**.

In some embodiments, the magnetic field measuring system **300**B further includes a moving device (not shown in figures) configured to control the particle PB**3**. The moving device controlling the particle PB**3** is configured to adjust a distance between the particles PB**1** and PB**3**, to adjust the coupling strength GB**3**. The moving device controlling the particle PB**3** is further configured to adjust the distance between the particles PB**2** and PB**3**, to adjust the coupling strength GB**2**. The moving device controlling the particle PB**3** is further configured to adjust the distance between the particles PB**4** and PB**3**, to adjust the coupling strength GB**6**.

In some embodiments, the magnetic field measuring system **300**B further includes a moving device (not shown in figures) configured to control the particle PB**4**. The moving device controlling the particle PB**4** is configured to adjust a distance between the particles PB**1** and PB**4**, to adjust the coupling strength GB**4**. The moving device controlling the particle PB**4** is further configured to adjust the distance between the particles PB**2** and PB**4**, to adjust the coupling strength GB**5**. The moving device controlling the particle PB**4** is further configured to adjust the distance between the particles PB**4** and PB**3**, to adjust the coupling strength GB**6**.

FIG. **4** is a schematic diagram of a magnetic field measuring apparatus **400** illustrated according to one embodiment of the present disclosure. In some embodiments, the magnetic field measuring apparatus **400** includes a sensing block **410**, a moving device **420** and a laser generating device group **430**. As illustratively shown in FIG. **4**, the sensing block **410**, the laser generating device group **430** and the moving device **420** are arranged in order along the Z direction.

In some embodiments, the sensing block **410** is configured to sense a magnetic field B**4** applied to the sensing block **410**. The laser generating device group **430** is configured to emit lasers Z**1**-Z**12** toward an opposite direction of the Z direction, to the sensing block **410**. The moving device **420** is configured to move the laser generating device group **430**. In some embodiments, a direction of the magnetic field B**4** is the Z direction.

In some embodiments, the sensing block **410** includes sensing module columns CL**1**-CL**6**. In some embodiments, each of the sensing module columns CL**1**-CL**6** is configured to sense a strength of the magnetic field B**4** surrounding thereof. As illustratively shown in FIG. **4**, the sensing module columns CL**1**-CL**6** are arranged in order along an X direction different from the Z direction. In some embodiments, the X direction is perpendicular with the Z direction.

In some embodiments, the laser generating device group **430** includes laser generating devices LG**1**-LG**6**. As illustratively shown in FIG. **4**, the laser generating devices LG**1**-LG**6** arranged in order along the X direction. The laser generating device LG**1** is configured to emit lasers Z**1** and Z**2** to the sensing module column CL**1**. The laser generating device LG**2** is configured to emit lasers Z**3** and Z**4** to the sensing module column CL**2**. The laser generating device LG**3** is configured to emit lasers Z**5** and Z**6** to the sensing module column CL**3**. The laser generating device LG**4** is configured to emit lasers Z**7** and Z**8** to the sensing module column CL**4**. The laser generating device LG**5** is configured to emit lasers Z**9** and Z**10** to the sensing module column CL**5**. The laser generating device LG**6** is configured to emit lasers Z**11** and Z**12** to the sensing module column CL**6**.

In some embodiments, the moving device **420** is configured to move the laser generating devices LG**1**-LG**6** to adjust positions of the sensing module columns CL**1**-CL**6**. For example, as illustratively shown in FIG. **4**, a distance D**41** is between the sensing module columns CL**6** and CL**5**. The moving device **420** is configured to move the laser generating device LG**5** toward the laser generating device LG**6**, to decrease the distance D**41**. For another example, the moving device **420** is configured to move the laser generating device LG**5** away from the laser generating device LG**6**, to increase the distance D**41**.

In some approaches, the space resolution of measuring devices performing fine measurements to magnetic fields is limited by manufacturing process, and cannot be changed easily.

Compare to above approaches, in some embodiments of present disclosure, the moving device **420** may adjust the positions of the sensing module columns CL**1**-CL**6**, to adjust the space resolution of the magnetic field measuring apparatus **400**. As a result, user can optimize the magnetic field measuring apparatus **400** according to the magnet field B**4** which is desired to be measured.

In some embodiments, each of the sensing module columns CL**1**-CL**6** includes multiple sensing modules arranged in order along the Z direction. Each of the sensing modules described above is configured to sense a strength of the magnetic field B**4** surrounding thereof. In the embodiment shown in FIG. **4**, the sensing module column CL**6** includes sensing modules **411**, **412** and other two sensing modules. The sensing module column CL**5** includes a sensing module **413** and other three sensing modules. The sensing modules **412** and **411** are arranged in order along the Z direction. The sensing modules **413** and **411** are arranged in order along the X direction.

Referring to FIG. **1** and FIG. **4**, the magnetic field measuring apparatus **400** is an alternative embodiment of the magnetic field measuring apparatus **100**. The moving devices **120** and **130** correspond to the moving device **420**.

The laser generating devices **140** and **150** correspond to the laser generating devices LG**1**-LG**6**. The light emitting device **110**, the sensing device **180**, the particles PT**1**, PT**2**, the fixing device **160**, **170** and the processing device **190** correspond to the sensing modules in the sensing module columns CL**1**-CL**6**. The lasers Z**1**-Z**12** correspond to the lasers LZ**1** and LZ**2**. Therefore, some descriptions are not repeated for brevity.

For example, in some embodiments, the sensing module **412** includes the light emitting device **110**, the sensing device **180**, the particles PT**1**, PT**2**, the fixing devices **160**, **170** and the processing device **190**. The laser generating device LG**6** includes the laser generating devices **140** and **150**. The lasers Z**11** and Z**12** correspond to the lasers LZ**1** and LZ**2**, respectively. The laser Z**11** is configured to fix the fixing device **170**. The laser Z**12** is configured to fix the fixing device **160**. The moving device **420** includes the moving device **120** and **130**. A distance between the lasers Z**11** and Z**12** corresponds to the distance D**1**. The sensing module **412** is configured to measure the strength of the magnetic field B**4** surrounding the sensing module **412**, according to the coupling strength G**1** between the particles PT**1** and PT**2**.

For another example, in some embodiments, the sensing module **411** includes the light emitting device **110**, the sensing device **180**, the particles PT**1**, PT**2**, the fixing devices **160**, **170** and the processing device **190**. The laser generating device LG**6** includes the laser generating devices **140** and **150**. The lasers Z**11** and Z**12** correspond to the lasers LZ**1** and LZ**2**, respectively. The laser Z**11** is configured to fix the fixing device **170**. The laser Z**12** is configured to fix the fixing device **160**. The moving device **420** includes the moving device **120** and **130**. A distance between the lasers Z**11** and Z**12** corresponds to the distance D**1**. The sensing module **411** is configured to measure the strength of the magnetic field B**4** surrounding the sensing module **411**, according to the coupling strength G**1** between the particles PT**1** and PT**2**. In some embodiments, particles in the sensing modules **411** and **412** are positioned by the same lasers Z**11** and Z**12**.

In some embodiments, other sensing modules in the sensing module columns CL**1**-CL**6** have configurations similar with the configurations of the sensing module **412** described above. For example, the sensing module **413** includes a first particle corresponding to the particle PT**1** and a second particle corresponding to the particle PT**2**. The laser Z**9** is configured to fix the first particle. The laser Z**10** is configured to fix the second particle. The moving device **420** is configured to move positions of the lasers Z**9** and Z**10** to adjust a coupling strength between the first particle and the second particle. The sensing module is configured to calculate a strength of the magnetic field B**4** surrounding the sensing module **413**, according to the coupling strength between the first particle and the second particle.

In some embodiments, the moving device **420** is further configured to move positions of the lasers Z**11** and Z**10**, to adjust the distance D**41** between the second particle and the particle PT**1** in the sensing module **412**, to adjust the space resolution of the magnetic field measuring apparatus **400**.

As illustratively shown in FIG. **4**, the sensing module in the sensing module columns CL**1**-CL**6**, such as the sensing module **412**, is configured to perform a method **499**. The method **499** includes operations OP**41**-OP**44**.

In some embodiments, at the operation OP**41**, radical pairs are prepared. For example, the particles PT**1** and PT**2** having the radical pairs RP**1** and RP**2** are fixed by the fixing devices **170** and **160**, and the distance D**1** is adjusted by the moving devices **120** and **130**.

In some embodiments, at the operation OP**42**, output lights of the radical pairs are measured. For example, the sensing device **180** performs the measurements to the strengths of the output lights L**13** and L**14**.

In some embodiments, at the operation OP**43**, a readout signal is generated according to the output lights. For example, the sensing device **180** generates the readout signal BS**1** according to the strengths of the output lights L**13** and L**14**.

In some embodiments, at the operation OP**44**, the strength of the magnetic field is calculated according to the readout signal. For example, the processing device **190** performs the calculations according to the readout signal BS**1** and the equations (1)-(8), to calculate the strength of the magnetic field B**1** or B**4**. In various embodiments, the processing device **190** may be located at inside or outside of the sensing module **412**.

Although the present disclosure has been described in considerable detail with reference to certain embodiments thereof, other embodiments are possible. Therefore, the spirit and scope of the appended claims should not be limited to the description of the embodiments contained in the present disclosure.

It will be apparent to those skilled in the art that various modifications and variations can be made to the structure of the present disclosure without departing from the scope or spirit of the disclosure. In view of the foregoing, it is intended that the present disclosure cover modifications and variations of the present disclosure provided they fall within the scope of the following claims.

What is claimed is:

1. A magnetic field measuring method, comprising:

applying a magnetic field to a first particle and a second particle;

generating a first output light by the first particle according to the magnetic field and a first coupling strength between the first particle and the second particle;

calculating a strength of the magnetic field according to a strength of the first output light;

fixing the first particle by a first laser; and

fixing the second particle by a second laser,

wherein generating the first output light comprises adjusting a distance between the first particle and the second particle, to adjust the first coupling strength, and

adjusting the distance comprises adjusting at least one of a position of the first laser and a position of the second laser.

2. The magnetic field measuring method of claim **1**, wherein generating the first output light further comprises:

adjusting the strength of the first output light by adjusting the first coupling strength.

3. The magnetic field measuring method of claim **2**, wherein a direction of the magnetic field is perpendicular with the distance.

4. The magnetic field measuring method of claim **1**, wherein calculating the strength of the magnetic field comprises:

generating a readout signal according to the strength of the first output light; and

calculating the strength of the magnetic field according to at least one coupling strength value of the first coupling strength corresponding to at least one local peak value of the readout signal.

5. The magnetic field measuring method of claim **1**, further comprising:

applying the magnetic field to a third particle,

wherein generating the first output light comprises:

generating the first output light according to a second coupling strength between the third particle and the second particle and a third coupling strength between the third particle and the first particle.

6. The magnetic field measuring method of claim **1**, further comprising:

generating a second output light by the second particle according to the first coupling strength; and

calculating the strength of the magnetic field according to a strength of the second output light.

7. The magnetic field measuring method of claim **1**, wherein the first coupling strength is a coupling strength between a radical of a first radical pair and a radical of a second radical pair.

8. A magnetic field measuring system, comprising:

a first particle configured to generate a first output light according to a first coupling strength and a magnetic field;

a second particle configured to be coupled to the first particle with the first coupling strength;

a sensing device configured to generate a readout signal corresponding to a strength of the magnetic field according to a strength of the first output light; and

a first fixing device comprising a first fixing body and a first line segment, the first line segment connecting the first fixing body and the first particle, to fix the first particle.

9. The magnetic field measuring system of claim **8**,

wherein a distance between the first particle and the second particle is adjust, to adjust the first coupling strength,

wherein the distance is perpendicular with a direction of the magnetic field.

10. The magnetic field measuring system of claim **9**, further comprising:

a processing device configured to calculate the strength of the magnetic field according to at least one coupling strength value of the first coupling strength corresponding to at least one local peak value of the readout signal, after the distance is adjusted.

11. The magnetic field measuring system of claim **9**, further comprising:

a first laser generating device configured to generate a first laser to position the first fixing device in space.

12. The magnetic field measuring system of claim **11**, further comprising:

a second fixing device comprising a second fixing body and a second line segment, the first line segment connecting the second fixing body and the second particle, to fix the second particle; and

a second laser generating device configured to generate a second laser to position the second fixing device in space.

13. The magnetic field measuring system of claim **8**, further comprising:

a third particle configured to be coupled to the first particle with a second coupling strength, and configured to be coupled to the second particle with a third coupling strength,

wherein the first particle is further configured to generate the first output light according to the second coupling strength and the third coupling strength.

14. The magnetic field measuring system of claim **13**, further comprising:

a fourth particle configured to be coupled to the first particle with a fourth coupling strength, configured to be coupled to the second particle with a fifth coupling strength, and configured to be coupled to the third particle with a sixth coupling strength,

wherein the first particle is further configured to generate the first output light according to the fourth coupling strength, the fifth coupling strength and the sixth coupling strength.

15. The magnetic field measuring system of claim **8**, wherein

the first particle comprises a first radical pair comprising a first radical and a second radical,

the second particle comprises a second radical pair comprising a third radical and a fourth radical,

the first coupling strength is a coupling strength between the second radical and the third radical,

a distance between the first radical and the third radical is larger than a distance between the second radical and the third radical, and

a distance between the second radical and the fourth radical is larger than the distance between the second radical and the third radical.

16. A magnetic field measuring apparatus, comprising:

a first sensing module configured to calculate a first strength of a magnet field surrounding the first sensing module;

a second sensing module configured to calculate a second strength of the magnet field surrounding the second sensing module;

a first laser generating device configured to position the first sensing module; and

a second laser generating device configured to position the second sensing module,

wherein at least one of the first laser generating device and the second laser generating device is moved, to adjust a distance between the first sensing module and the second sensing module.

17. The magnetic field measuring apparatus of claim **16**, wherein the first sensing module comprising:

a processing device configured to calculate the first strength of the magnet field surrounding the first sensing module according to a coupling strength between a first particle and a second particle,

wherein the first laser generating device is further configured to generate a laser, and fix the first particle by the laser.

18. The magnetic field measuring apparatus of claim **17**, wherein a direction of the laser is perpendicular with a direction of the distance.

19. The magnetic field measuring apparatus of claim **17**, further comprising:

a third sensing module comprising a third particle and a fourth particle, the third sensing module configured to calculate a third strength of the magnet field surrounding the third sensing module according to a coupling strength between the third particle and the fourth particle,

wherein the first laser generating device is further configured to fix the third particle by the laser.

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