

OPTICALLY PUMPED MAGNETOMETER

TECHNOLOGICAL FIELD

The present disclosure, in some embodiments, thereof, relates to magnetometers and, more particularly, but not exclusively, to optically pumped magnetometers (OPMs).

BACKGROUND ART

5 Page 11 of reference [12] as listed below, states:

“The Cesium alkali vapor magnetometer offers good sensitivity and bandwidth (about 10 pT $\sqrt{\text{Hz}}$) but has a few disadvantages, including heading errors. As described previously, Cesium’s spectral lines are wide, meaning that the electron energy levels associated with the Zeeman effect vary widely in magnitude over a population of Cesium
10 *atoms. In static conditions (i.e. the orientation of the magnetic field is stationary), a peak becomes apparent, and the system will self oscillate at this peak.*

When the magnetic field direction changes, however, the position of this peak will change because the spectral line amplitudes change. As a result, the self-oscillating frequency will shift, producing a heading error. Since Cesium’s spectral lines are spread
15 *over some 20 nT, the heading error could be that severe.”*

“In static conditions (i.e. the orientation of the magnetic field is stationary), a peak becomes apparent, and the system will self-oscillate at this peak. When the magnetic field direction changes, however, the position of this peak will change because the spectral line amplitudes change. As a result, the self-oscillating frequency will shift,
20 *producing a heading error.”*

Reference [13] as listed below, states *“The frequency shifts of a self-oscillating magnetometer with cesium vapor are studied quantitatively by solving rate equations for cesium atoms undergoing the action of a circularly polarized pumping light beam. Particular attention is given to the frequency shifts due to the line asymmetry of the rf*
25 *spectrum in the light transmitted through the vapor. The line asymmetry varies with the orientation of the light beam relative to the field to be measured, the intensity of the light, and the temperature of the absorption cell. As an effect of a buffer gas, two extreme cases*

are considered, i.e., the optically excited state is in the complete mixing state and in the nonmixing state. The results show the fact that the frequency shifts depend largely on the collisional mixing in the excited state and on the sense of the circular polarization of the light. In order to reduce the frequency shifts, a new type of magnetometer, called the
 5 symmetrized spectrum magnetometer, is discussed, in which two circularly polarized light beams with opposite sense are simultaneously applied to a partitioned absorption cell.”

Background art, where each art is incorporated in its entirety by reference, includes the below list. In the following document these arts are referred to by number e.g. using the relevant reference number/s in square brackets: [number].

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Acknowledgement of the above references herein is not to be inferred as meaning that these are in any way relevant to the patentability of the presently disclosed subject matter.

10 GENERAL DESCRIPTION

Following is a non-exclusive list of some exemplary embodiments of the disclosure. The present disclosure also includes embodiments which include fewer than all the features in an example and embodiments using features from multiple examples, even if not listed below.

- 15 Example 1. A magnetic field strength measurement system comprising:
a vapor chamber holding alkali metal vapor;
a light source unit configured to supply circularly polarized laser light and positioned to feed a first pass beam of said circularly polarized light into said vapor chamber;
20 a retroflection unit comprising least one optical element and configured to reverse a direction, while maintaining polarization, of said first pass beam upon exit from said vapor chamber to provide a second pass beam to said vapor chamber, said second pass beam having an opposite direction, and same circular polarization as said first pass beam;
a detector positioned to measure light emitted from said vapor chamber; and
25 circuitry configured to:
provide a modulating signal to said source, said modulating signal configured to modulate said first pass beam;
receive a measurement signal from said detector;
demodulate said measurement signal using said modulating signal to
30 provide a demodulated measurement signal; and
determine a resonance frequency from one or both of said modulating signal and said demodulated measurement signal.

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Example 2. The system according to Example 1, wherein said circuitry is configured to provide said modulation signal at a plurality of modulation frequencies, wherein said demodulated measurement signal comprises a plurality of amplitudes each amplitude associated with a frequency of said plurality of modulation
5 frequencies.

Example 3. The system according to Example 1, wherein said circuitry is configured to extract a resonance frequency from said demodulated measurement signal.

Example 4. The system according to Example 3, wherein said circuitry comprises a lock-in amplifier configured to receive said measurement signal and said
10 modulating signal and outputting said demodulated measurement signal.

Example 5. The system according to Example 3, wherein said demodulated measurement signal comprises a quadrature plot and where said circuitry is configured to extract a resonance frequency as a zero-crossing of a said quadrature plot.

Example 6. The system according to Example 1, wherein said circuitry is
15 configured to use said demodulated measurement signal as feedback to said modulation signal to maintain said demodulated measurement signal at a set value, where said resonance frequency is extracted as a steady state frequency of said modulation signal.

Example 7. The system according to any one of Examples 1-6, wherein said light source unit comprises a laser source of linearly polarized light and one or more
20 optical element configured to convert the linearly polarized light into circularly polarized light.

Example 8. The system according to any one of Examples 1-7, wherein said first pass beam is fed to said vapor chamber in a first direction and where said retroreflector is positioned to reverse a direction of said first pass beam to provide said second pass
25 beam.

Example 9. The system according to any one of Examples 1-8, comprising a loss compensation unit configured to increase a resonance light signal produced by said vapor chamber and associated with said second pass beam.

Example 10. The system according to Example 9, wherein said compensation
30 unit comprises at least one heater configured to heat at least a portion of said alkali metal vapor through which said second pass beam passes.

Example 11. The system according to any one of Examples 9-10, wherein said loss compensation unit comprises one or more temperature controller configured to control temperature of one or more portion of said vapor chamber.

Example 12. The system according to any one of Examples 9-11, wherein said
5 loss compensation unit comprises one or more beam broadening element in a path of said second pass beam prior to entry of said second pass beam to said vapor chamber as said second pass beam.

Example 13. The system according to any one of Examples 1-12, wherein said detector comprises a photodiode.

10 Example 14. The system according to any one of Examples 1-13, wherein said retroreflector unit comprises at least two light diverting elements.

Example 15. The system according to Example 14, wherein each of said at least two light diverting element comprises a reflecting prism or a mirror.

15 Example 16. The system according to any one of Examples 14-15, wherein said at least two light diverting elements comprises three light diverting elements.

Example 17. A method of magnetic field strength measurement comprising:
supplying a first beam of circularly polarized light and a second beam of circularly polarized light to a pumped vapor chamber holding alkali metal vapor;
measuring light emitted from said vapor chamber to provide one or more
20 measurement signal;

controlling one or more of temperature of one or more portion of said alkali metal vapor and beam cross sectional area of one or more of said first beam and said second beam.

25 Example 18. The method according to Example 17, comprising determining a magnetic resonance frequency from said measurement signal.

Example 19. The method according to Example 18, comprising determining the magnetic field strength using said magnetic resonance frequency.

Example 20. A system of magnetic field strength measurement system comprising:
30 a vapor chamber holding alkali metal vapor;
a source of laser light;

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one or more optical element configured to receive said laser light and provide a first circularly polarized beam of light and a second circularly polarized beam of light to said vapor chamber;

one or more sensor configured to measure one or more of:

- 5 said first circularly polarized beam of light;
 said second circularly polarized beam of light;
 light emitted from said vapor chamber;

a compensation unit comprising one or more temperature controller and one or more beam area controller;

- 10 a controller configured to receive one or more measurement from said one or more sensor and to provide control signals to said compensation unit.

Example 21. A method of measuring magnetic field strength comprising:

providing a modulating signal at a plurality of modulation frequencies;

- 15 directing a first pass beam of circularly polarized light into a vapor chamber of pumped alkali metal atoms in a first direction, where said first pass beam is modulated according to said modulating signal;

reversing a direction, while maintaining polarization, of said first pass beam upon exit from said vapor chamber to provide a second pass beam to said vapor chamber, said second pass beam having an opposite direction, and same circular polarization as said

- 20 first pass beam;

acquiring a measurement signal of light emitted from said vapor chamber;

demodulating said measurement signal using said modulating signal to provide a demodulated measurement signal;

- 25 determining a resonance frequency from one or both of said modulating signal and said demodulated measurement signal.

Example 22. The method according to Example 21, wherein said demodulated measurement signal comprises a plurality of amplitudes, each amplitude associated with a frequency of said plurality of modulation frequencies.

- Example 23. The method according to Example 21, wherein said determining
30 said resonance frequency comprises extracting said resonance frequency from said demodulated measurement signal.

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Example 24. The method according to Example 23, wherein demodulated measurement signal comprises a quadrature plot and where said determining said resonance frequency comprises extracting a zero-crossing of a said quadrature plot.

Example 25. The method according to Example 21, comprising using said
5 demodulated measurement signal as feedback to said modulation signal to maintain said demodulated measurement signal at a set value, where said resonance frequency is extracted as a steady state frequency of said modulation signal.

Example 26. The method according to any one of Examples 21-25, comprising
10 compensating loss to said second pass beam to increase a resonance light signal produced by said vapor chamber and associated with said second pass beam.

Example 27. The method according to Example 26, wherein said compensating loss comprises receiving a measurement from one or more sensor.

Example 28. The method according to Example 27, wherein said compensating loss comprises controlling a temperature, based on said measurement from one or more
15 sensor, of at least a part of a portion of said alkali metal vapor through which said second pass beam passes.

Example 29. The method according any one of Examples 27-28, wherein said compensating loss comprises controlling a beam cross area of said second pass beam, based on said measurement from one or more sensor.

20 Unless otherwise defined, all technical and/or scientific terms used within this document have meaning as commonly understood by one of ordinary skill in the art/s to which the present disclosure pertains. Methods and/or materials similar or equivalent to those described herein can be used in the practice and/or testing of embodiments of the present disclosure, and exemplary methods and/or materials are described below.
25 Regarding exemplary embodiments described below, the materials, methods, and examples are illustrative and are not intended to be necessarily limiting.

Some embodiments of the present disclosure are embodied as a system, method, or computer program product. For example, some embodiments of the present disclosure may take the form of an entirely hardware embodiment, an entirely software embodiment
30 (including firmware, resident software, micro code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a “circuit,” “module” and/or “system.”

Implementation of the method and/or system of some embodiments of the present disclosure can involve performing and/or completing selected tasks manually, automatically, or a combination thereof. According to actual instrumentation and/or equipment of some embodiments of the method and/or system of the present disclosure, 5 several selected tasks could be implemented by hardware, by software or by firmware and/or by a combination thereof, e.g., using an operating system.

For example, hardware for performing selected tasks according to some embodiments of the present disclosure could be implemented as a chip or a circuit. As software, selected tasks according to some embodiments of the present disclosure could 10 be implemented as a plurality of software instructions being executed by a computational device e.g., using any suitable operating system.

In some embodiments, one or more tasks according to some exemplary embodiments of method and/or system as described herein are performed by a data processor, such as a computing platform for executing a plurality of instructions. 15 Optionally, the data processor includes a volatile memory for storing instructions and/or data and/or a non-volatile storage e.g., for storing instructions and/or data. Optionally, a network connection is provided as well. User interface/s e.g., display/s and/or user input device/s are optionally provided.

Some embodiments of the present disclosure may be described below with 20 reference to flowchart illustrations and/or block diagrams. For example illustrating exemplary methods and/or apparatus (systems) and/or and computer program products according to embodiments of the present disclosure. It will be understood that each step of the flowchart illustrations and/or block of the block diagrams, and/or combinations of steps in the flowchart illustrations and/or blocks in the block diagrams, can be 25 implemented by computer program instructions. These computer program instructions may be provided to a processor of a general-purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the 30 flowchart steps and/or block diagram block or blocks.

These computer program instructions may also be stored in a computer readable medium that can direct a computer (e.g., in a memory, local and/or hosted at the cloud), other programmable data processing apparatus, or other devices to function in a particular

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manner, such that the instructions stored in the computer readable medium can be used to produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

The computer program instructions may also be run by one or more computational
5 device to cause a series of operational steps to be performed e.g., on the computational device, other programmable apparatus and/or other devices to produce a computer implemented process such that the instructions which execute provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

10 Some of the methods described herein are generally designed only for use by a computer, and may not be feasible and/or practical for performing purely manually, by a human expert. A human expert who wanted to manually perform similar tasks, might be expected to use different methods, e.g., making use of expert knowledge and/or the pattern recognition capabilities of the human brain, potentially more efficient than
15 manually going through the steps of the methods described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by
20 way of non-limiting example only, with reference to the accompanying drawings, in which:

FIG. 1 is a simplified schematic block diagram of a magnetometer system, according to some embodiments of the disclosure;

FIGs. 2A-D illustrate magnetic resonance plots, according to some embodiments
25 of the disclosure;

FIG. 3 is a simplified schematic portion of a band diagram for an alkali metal, according to some embodiments of the disclosure;

FIGs. 4A-B are a simplified schematics of Zeeman level populations, according to some embodiments of the disclosure;

30 FIGs. 5A-B are plots of resonance line-shapes for different Zeeman levels of the $F=4$ states, according to some embodiments of the disclosure;

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FIG. 6 is a plot of magnetic resonance frequency with angle between laser propagation vector and magnetic field, according to some embodiments of the disclosure;

FIG. 7 is a method of measuring a magnetic field, according to some embodiments of the disclosure;

5 FIG. 8A is a simplified schematic block diagram of a portion of a magnetometer system, according to some embodiments of the disclosure;

FIG. 8B is simplified schematic a cross sectional view of a portion of a magnetometer system, according to some embodiments of the disclosure;

10 FIG. 8C is a cross sectional view of a portion of a retroflection unit, according to some embodiments of the disclosure;

FIG. 9A is a simplified schematic of a split beam configuration magnetometer system, according to some embodiments of the disclosure; and

FIG. 9B is a cross sectional view of a portion of a magnetometer system, according to some embodiments of the disclosure.

15 In some embodiments, although non-limiting, in different figures, like numerals are used to refer to like elements, for example, element **102** in FIG. 1 corresponding to element **802** in FIG. 8.

DETAILED DESCRIPTION OF EMBODIMENTS

20 The present disclosure, in some embodiments, thereof, relates to magnetometers and, more particularly, but not exclusively, to optically pumped magnetometers (OPMs).

Overview

25 An aspect of some embodiments of the disclosure relates to optically pumped magnetometers (OPM) and/or magnetic measurement systems where a beam of laser pumping light traverses a transparent (e.g., glass) cell containing alkali metal vapor (herein termed a “vapor chamber” or a “vapor cell”) twice (herein termed a “first pass beam” and a “second pass beam”) in different (e.g. opposite) directions. Where, for the two passages of light through the vapor chamber, the light beams have the same circular polarization helicity.

30 Two passages through the vapor chamber of a single beam (also herein termed a “double-pass configuration”) is achieved, in a possible configuration, by illuminating the

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vapor cell with a laser beam, where light exiting the vapor cell is herein termed the “transmitted laser beam”, and reflecting the transmitted laser beam herein termed a “reflected beam” back into the vapor chamber, to form the second pass beam.

In some embodiments, the magnetometer (and/or magnetic measurement system)
5 includes a single beam for both pumping and probing of the atoms in the vapor chamber.

Alternatively, in some embodiments, a first laser beam pumps the vapor chamber and a second laser beam, a “probe beam” is passed twice through the vapor chamber (e.g. a transmitted probe beam being reflected back into the vapor chamber).

In some embodiments, a light source unit configured to provide circularly
10 polarized light is positioned on a first side of the vapor cell, and a retroreflection unit is positioned on a second side of the cell and are aligned (e.g. with the laser source and/or vapor cell) to reflect the source beam emitted from the vapor cell (the transmitted beam) to the vapor cell as the second pass beam.

Where, in some embodiments, the retroreflection unit is comprises one or more
15 optical elements configured to reverse a received beam direction while maintaining the beam’s polarization, for example, the second pass beam, having a reversed direction to that of the first pass beam and circular polarization of the same helicity as the first pass beam. For example, where the k-vectors of the entering and reflected beams have opposite sign and where the entering and reflected beams have the same helicity e.g. both left-
20 handed circular polarization, or both right-handed circular polarization. Where, in some embodiments, the light source unit e.g. including a linearly polarized laser source and optical element/s configured to convert the linearly polarized light into circularly polarized light).

A potential benefit of two passages of light through the vapor chamber, the first
25 pass beam and second pass beam having the same polarization but different directions, being reduction in heading error. Where heading error is defined, for example, as a change in magnetic field measurements of the magnetometer with change in angle between a direction of laser propagation through the vapor chamber and a direction of the magnetic field being measured. For example, where the magnetic field remains the same but an
30 orientation of the magnetometer changes in space, without changing position (e.g. coordinates in space) of the magnetometer (e.g. rotation of the magnetometer about its center). For example, where the magnetic field changes direction, with respect to the magnetometer, without changing in magnitude.

Without wanting to be bound by theory, it is theorized that the double-pass configuration compensates for non-linearity of Zeeman splitting. For example, compensating for differences in population distribution of Zeeman states associated with different angles between the laser propagation vector and magnetic field direction vector.

5 As the population distribution changes, it is theorized, are opposite for the first and second pass beams, heading errors of the source beam and returning beam potentially cancel each other.

A potential advantage of the double-pass configuration is, for a given optical pathway length within the vapor chamber, increased signal amplitude potentially

10 providing higher signal to noise ratio (SNR) for the magnetic field measurement. For example, in comparison to a single pass configuration.

Potentially, increased SNR for given optical pathway length within the vapor chamber allows reduction in size of the vapor chamber and potentially, increased portability. Potentially, increased SNR enables one or more of reduction of the vapor

15 chamber temperature and reduction of laser power of the source beam.

A broad aspect of some embodiments of the disclosure relates to a magnetometer system where two beams of light are fed to a vapor chamber, where effect of one or both of the beams of emitted light from the vapor chamber is controlled to balance the effect of the beams.

20 In some embodiments, one of the beams is controlled. In some embodiments, both beams are controlled.

Where, in some embodiments, the effect of a beam is controlled by controlling a number of vapor atoms with which the beam interacts. For example, in some embodiments, one or both of temperature of a region of the vapor chamber through which

25 the beam passes and a cross sectional beam area of the beam within the vapor chamber are adjusted to control effect of the beam.

Alternatively or additionally, in some embodiments, the effect of the beam is controlled by controlling a power of the beam within the vapor chamber (e.g. as controlled by a power of the laser beam (e.g. controlled at the laser providing the beam).

30 With respect to the double-path configuration, for example, as the first pass beam is expected to experience loss/es during passage through the vapor chamber and/or during interaction between optical elements as the transmitted first pass beam is directed backward as the reflected beam to become the second pass beam, the effect of the second

pass beam on the alkali metal vapor of the vapor chamber is adjusted. For example, by controlling temperature of (e.g. heating) a portion of the alkali metal vapor through which the second pass beam passes (e.g. to a higher temperature than the portion of the alkali metal vapor through which the first pass beam passes). For example, additionally or
5 alternatively, by adjusting (e.g. broadening and/or increasing) the reflected beam cross-sectional area e.g. prior to it entering the vapor chamber as the second pass beam.

In some embodiments, a split-beam configuration magnetometer system includes a source unit which is configured to provide a first and a second beam of light, where both beams have a same general direction (e.g. propagation vector), but opposite circular
10 polarization.

In some embodiments, effect of each of the first and second beams on light within the vapor chamber is measured separately (e.g. a first detector providing a first measurement signal and a second detector providing a second measurement signal) where the two measurement signals are used to determine a resonance frequency associated with
15 the magnetic field. Without wanting to be bound by theory, it is theorized that, associated with the same direction and different circular polarization of the first and second beams, heading error of the first and second beams have opposite heading error. Where, potentially, using the two measurement signals to determine the resonance frequency, provides a reduced heading error measurement of magnetic field.

An aspect of some embodiments of the disclosure relates to controlling one or both of the first and second beams of the split-beam configuration magnetometer system. For example, by temperature control (e.g. heating) of portion/s of the vapor chamber and/or controlling beam cross sectional areas. Where, in some embodiments, the first and/or second measurement signals are used in closed loop control of the beam/s (e.g.
20 provide feedback to the control of the beams).

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings and/or the Examples. The
30 invention is capable of other embodiments or of being practiced or carried out in various ways.

Exemplary magnetometer system

FIG. 1 is a simplified schematic block diagram of a magnetometer system **100**, according to some embodiments of the disclosure.

In some embodiments, magnetometer system **100** (herein also termed “magnetometer” or “system”) includes a light source unit **102** which is configured to
5 produce circularly polarized laser light **104**. Where, in some embodiments, laser light source **102** includes a source of linearly polarized laser light (e.g., includes a sVCSEL laser, or DFB/DBR laser), and one or more element configured to transform linearly polarized light into circularly polarized light **104** (for example, the element/s including optical circular polarizer/s, e.g., a $\lambda/4$ waveplate). Where light **104**, in some embodiments
10 passes into a vapor chamber **106**.

Vapor chamber **106**, in some embodiments, includes a housing **108** which is formed of or includes transparent (e.g. to laser light) portion/s. Where light passing into vapor chamber **106** passes through a transparent portion of housing **108**. In some embodiments, housing **108**, holds a mixture **134** of vaporized alkali metal atoms and a
15 buffer gas/es.

Exemplary alkali metals including any one of the Alkali metal atoms appearing in the first column of the periodic table and/or helium (i.e., the Alkali metals Li, Na, K, Rb, Cs and Fr). Exemplary buffer gases include N_2 , and He.

Magnetic field measurements, in some embodiments, are acquired by “pumping”
20 the alkali vapor using circularly polarized laser light **104** emitted by light source **102**. Where laser light **104** enters and interacts with material **134** within vapor chamber **106**. Pumping, it is theorized, causes the projection of the angular momentum for the alkali vapor atoms to accumulate in a “stretch state”, corresponding to Zeeman level $m_F=F$.

Once the alkali atoms are pumped, light outputted **136** from vapor chamber **106**
25 is affected by the magnetic field: alkali atoms precess, it is theorized, under a magnetic field, according to the Larmor precession frequency, which frequency is associated with the Zeeman level of the atom precessing and the magnetic field strength.

In some embodiments (for example, once vapor chamber **106** is pumped by light **104**) a portion **136** of light **104** emitted by laser source **102** passes through vapor chamber
30 **106**.

In some embodiments, retroreflection unit **110** is configured to reverse a direction of received light **136**, whilst maintaining a helicity of light **136**. To direct back towards vapor chamber **106** second pass light **112** (also herein termed “reflected beam” light)

having a reversed direction (light propagation vector **k1** of light **104** and light propagation vector **k2** of second pass light **112**) and the same helicity as light **136** received by retroreflection unit **110**. For example, if light **104** includes right circular polarization light, second pass light **112** includes right circular polarization light.

5 Exemplary retroreflection unit **110** implementations are described with reference to FIG. 8C hereinbelow.

In some embodiments, magnetometer **100** includes a detector **126** which includes one or more optical sensor **126** configured to sense light **128** emanating from vapor chamber **106**. Sensor/s **126**, for example configured to provide an electrical signal
10 corresponding to light **128**. Where, in some embodiments, optical sensor/s **126** include one or more photodiode. Where the photodiode/s are configured to output an electrical signal corresponding to light sensed by the photodiode.

To measure the magnetic field, in some embodiments, laser light **104** is modulated, for example, by a modulation signal (e.g. provided by a current supply signal
15 to a laser of light source **102**).

In some embodiments, a modulation signal is scanned through a range of frequencies (continuously or with a plurality of discrete frequency values). Where a measurement signal (e.g. as provided by detector **126**) is demodulated, a resonance frequency being extracted from the demodulated measurement signal.

20 Alternatively, or additionally, in some embodiments, frequency of a modulation signal is controlled using feedback of the demodulation signal, where feedback is applied to maintain the demodulated signal at a set value (e.g. zero, corresponding to zero-crossing resonance frequency of the dispersive demodulation). Where the controlled frequency of the modulation signal is interpreted as corresponding to the resonance
25 frequency, e.g. in a steady state. For example, where upon a change in magnetic field and/or position of the magnetometer system, in some embodiments, the modulation signal fluctuates at a higher amplitude before falling to a low level of fluctuation. Where steady state is, in some embodiments, after a time period and/or at a low level of fluctuation (e.g. by less than 5% , or less than 1%) of the modulation signal.

30 Modulation of the modulation signal, in some embodiments, includes frequency modulation e.g. the laser's frequency is changing with time e.g. according to a frequency of the modulation signal. In some embodiments, frequency modulation is employed when the modulation signal is directly connected to a driver of the laser.

In some embodiments, modulation of the modulation signal is via amplitude modulation e.g. where the laser amplitude is changed with time. For example, turned on and off at the modulation frequency e.g. by a chopper element which blocks the laser light on and off.

5 In some embodiments, modulation of the modulation signal is via polarization modulation e.g. where the laser circular polarization is changed with time. For example, switched from left to right polarization at the modulation frequency.

In some embodiments, magnetometer includes processing and memory circuitry (PMC) **132**. Where, in some embodiments, PMC **132** receives sensor measurement data
10 e.g. from one or more optical sensor/s **126**, **146**, **147** and/or sensor/s of a loss compensation unit **114**. Where, in some embodiments, PMC **132** processes sensor measurements and, in some embodiments, generates control signals for loss compensation unit **114** and/or other elements controlled by PMC **132** e.g. laser **102**.

In some embodiments, a measurement signal (e.g. provided by detector **126**) is
15 demodulated (e.g. using the modulation signal e.g. at PCM **132**) to provide one or more demodulated measurement signal output with modulation frequency. Where, in some embodiments, demodulated measurement signals include one or more of an in-phase signal, a quadrature signal, a phase signal, and an amplitude signal. In some embodiments, demodulated measurement signal/s are generated by a lock-in amplifier (e.g. as an output
20 thereof). Where, in some embodiments, the lock-in amplifier's inputs include the measurement signal and the modulation signal. Where the lock-in amplifier's output includes one or more of an in-phase signal a quadrature signal, a phase signal and an amplitude signal. Lock-in amplifier output with modulation frequency plots are also herein termed "magnetic resonance plots" and "line-shapes". In some embodiments,
25 magnetic field strength is extracted as resonance frequency/ies of the one or more magnetic resonance plots.

In some embodiments, system **100** includes control for laser **102**.

In some embodiments, laser power **102** is controlled to provide equal vapor chamber signal amplitude from the transmitted **104** and reflected beams **116**.

30 Without wanting to be bound by theory it is theorized that amplitude of the vapor chamber signal depends laser power, but for a range of laser powers dependency is saturated e.g. where increase in laser power does not produce a corresponding rise in

signal amplitude. After saturation, it is theorized that further increase to the laser power results in a decrease in the signal amplitude.

In some embodiments, the laser power of light emitted **104** from laser **102** is controlled to provide amplitudes within a desired range. In some embodiments, the laser power is controlled by closed loop control, for example, as implemented by PMC **132** e.g. based on sensor measurement signal/s e.g. as received from sensors **146, 147**.

FIGs. 2A-D illustrate magnetic resonance plots, according to some embodiments of the disclosure.

10 In some embodiments, the magnetic resonance plots include one or both of a dispersive line-shape component (the quadrature) e.g. illustrated in FIG. 2A and a Lorentzian line-shape component (the in-phase) e.g. as illustrated in FIG. 2B.

Where, in some embodiments, the resonance frequency is extracted as a peak of the Lorentzian plot and/or as a zero-crossing of the quadrature plot. A potential benefit of using the quadrature zero-crossing to determine resonance frequency is potentially increased accuracy of extraction of the resonance frequency associated with a sharper response to change in magnetic field of the quadrature at the zero-crossing e.g. in comparison to that of the peak of the Lorentzian.

FIG. 2A and FIG. 2B, in some embodiments illustrate heading error, for example, as a difference in resonance frequency for different plots measuring different magnetic field directions (e.g. where the magnetic field has the same magnitude). For example, referring to FIG. 2A, in some embodiments, plots **266, 268** correspond to different magnetic field directions for a magnetic field having a same strength. Where a difference in frequency **264** of peaks **260, 262** is termed "heading error".

25 For example, referring to FIG. 2B, in some embodiments, plots **267, 269** correspond to different magnetic field directions for a magnetic field having a same strength. Where a difference in frequency between zero-crossings **261, 263** is termed "heading error".

Referring now to FIG. 2C which illustrates a Lorentzian magnetic resonance plot, according to some embodiments of the disclosure. Where plots **244, 254** illustrate magnetic resonance, referring to FIG. 1, associated with interaction of first pass light **104** and interaction of second pass light **112** respectively with material **134** within vapor

chamber **106**. Where a magnetic resonance plot **250** extracted from measurements at detector **126** may be considered to be a summation of plots **244**, **254**.

Without wanting to be bound by theory, it is theorized (e.g. as detailed hereinbelow) that first pass light **104** and associated plot **244** and second pass light **144** and associated plot **252** have heading error in opposite direction. Where measurement of interaction of both light beams **104**, **112** with material **134** in vapor chamber **106** provides magnetic resonance measurements (e.g. plot **256** having peak **250**) with reduced heading error. For example, a frequency of peak has reduced heading error e.g. than that of peaks **248**, **252** e.g. when magnetic field direction is changed, for the same field strength, the frequency of the measured peak of the double-pass configuration magnetometer system is lower than that of a single pass magnetometer system. This idea has been illustrated with respect to a Lorentzian magnetic resonance plot but, in some embodiments, is applied to a quadrature magnetic resonance plot.

Light propagation presents losses to the laser light beam **104** e.g. associated with absorption and/or scattering (e.g. at element/s of retroreflection unit **110**). Where, for example, in some embodiments, light **136** has lower power than light **104**. Where, for example, in some embodiments, light **112** has lower power than light **136**.

In some embodiments, losses to the laser light beam **104** are sufficient to affect measured magnetic resonance. For example, referring to FIG. 2D which illustrates a lowered amplitude of plot **255** (lowered from that of plot **254** FIG. 2C) corresponding to interaction of second pass light **112** with the material in the vapor chamber. The combination of plot **244** and plot **255** (combination of effects of the light beams **104**, **112** on the vapor chamber) illustrated by plot **257** which has a shifted peak **251** e.g. associated with increased heading error.

In some embodiments, magnetometer **100** includes a loss compensation unit **114**. Potentially, loss compensation unit **114** increases the interaction cross section of second pass beam **112** e.g. to increase amplitude contribution of second pass beam **112** to the magnetic resonance plot/s produced from detector **126** measurements.

Where loss compensation unit **114**, in some embodiments, increases a number of alkali atoms of vapor chamber **106** which are in a light path of second pass light **112**. Without wanting to be bound by theory it is theorized that a larger number of light beam-atom interactions increases an amplitude of a portion of the magnetic resonance measurement signal associated with the light beam in question.

In some embodiments, loss compensation unit **114** includes one or more temperature control unit (e.g. including one or more heater) configured to control temperature (e.g. heat) a portion **138** of vapor chamber **106** e.g. a portion of mixture **134** within chamber **106**. Where, in some embodiments, heated portion **138** includes a portion
5 through which second pass light **112** passes. Where, without wanting to be bound by theory, it is theorized, that heating of mixture **134** increases a number of alkali atoms in the path of second pass light **112**. For example, as vapor concentration is about exponential with temperature, e.g., about doubles for each 10°C increase in temperature.

Alternatively, or additionally, in some embodiments, loss compensation unit **114**
10 includes one or more beam broadening element. Where, for example, an increased cross sectional area beam of second pass light **112** increases the number of atom-beam interactions within vapor chamber **106**.

In some embodiments, temperature of more than one portion of the vapor chamber **106** is controlled using the one or more heater of loss compensation unit **114**. For
15 example, where both a portion of vapor chamber through which first pass light **104** and a portion of vapor chamber through which second pass light **112** passes are heated e.g. to different temperatures. Alternatively or additionally, a portion is heated and a second portion is cooled. Alternatively or additionally, a local temperature control unit heats a portion of the vapor chamber, while a second temperature control unit controls a
20 temperature of surroundings of the magnetometer system.

In some embodiments, loss compensation unit **114** includes one or more sensor.

In some embodiments, PMC **132** includes a compensation control unit, which, in some embodiments, receives sensor measurements processes the measurements, and generates control signals e.g. which are sent to one or more of loss compensation heater/s
25 and/or beam broadening element/s. For example, the measurement signals from sensor/s of loss compensation unit **114**, and/or from sensors **142** measuring light within system **100**.

Where, for example, in some embodiments, transmitted light **136** is measured. For example, where the transmitted light beam **136** is split (e.g. by a splitter **142**) where a
30 small portion (e.g. less than 5% or less than 1%) of the transmitted light beam is directed (e.g. away from a direction of beam **136**) to a sensor **146** which, in some embodiments, sends a measurement signal regarding transmitted light **136** to PCM.

Where, for example, in some embodiments, reflected light **116** is measured. For example, where the reflected light beam **116** is split (e.g. by a splitter **143**) where a small portion (e.g. less than 5% or less than 1%) of the reflected light beam is directed (e.g. away from a direction of beam **116**) to a sensor **147** which, in some embodiments, sends
 5 a measurement signal regarding reflected light **136** to PCM. Alternatively, or additionally to measurement of reflected light beam **116**, in some embodiments, reflected light beam **116** is measured after a cross section of the beam is adjusted.

Optionally, in some embodiments, magnetometer **100** includes one or more user interface (UI) **130**. Where, in some embodiments, UI **130** is configured to receive
 10 instruction/s and/or data (e.g. from a user) and transfer them to PMC **132**. Where, in some embodiments, UI **130** is configured to receive data from PMC **132** and, for example, display the data e.g. to user/s. The data displayed, for example, including determined measurement of magnetic field.

15 *Zeeman levels*

FIG. 3 is a simplified schematic portion of a band diagram for an alkali metal, according to some embodiments of the disclosure.

FIG. 3 illustrates fine structure energy levels (e.g. corresponding to interaction of the single electron in the outer shell of the alkali metal electron's orbital and spin angular
 20 momentum) where D1 is a transition between the fine structure energy levels.

FIG. 3 illustrates hyper-fine structure energy levels $F=3, 4$ and $F'=3, 4$ and Zeeman sublevels, associated with magnetic field, m_F, m'_F .

Theoretically, pumping of the alkali metal vapor using circularly polarized light (e.g. with beam **104**, FIG. 1) transfers outer electrons of the alkali metal vapor atoms to a
 25 Zeeman level of $m_F=F$, herein termed a "stretch state". It is theorized that interaction of the alkali metal atoms with a magnetic field causes the magnetic moment of these atoms to precess at the Larmor frequency. Where the Larmor frequency is associated with both the gyrometric ratio of the alkali atoms and the magnetic field. A peak of the magnetic resonance plot, theoretically, corresponding to the Larmor frequency, giving a measure
 30 of the magnetic field.

However, when the alkali metal vapor is pumped using circularly polarized light **104**, it is theorized that, in reality, the population of alkali metal atoms (also herein termed "vapor population") will not completely accumulate in the stretch state, $m_F = F$,

(referring to FIG. 3, the stretch state is $m_F = 4$). Meaning that each Zeeman level has a distinct population, n_{m_F} . Different populations in different Zeeman levels due, it is theorized, to the different hyper-fine levels and/or transition probabilities between the ground and excited state.

- 5 The vapor population of alkali atoms having proportions in different Zeeman levels affects the measured magnetic resonance plot, as each Zeeman level has a different Larmor frequency due to the non-linear Zeeman effect, also herein termed resonance frequency ω_{m_F} . Where, the measured magnetic resonance plot/s (e.g. illustrated in FIGs. 2A-D) illustrate collective behavior of the alkali metal atoms i.e., a weighted sum of the
- 10 different lineshapes with respect to the population in that Zeeman level.

Population distribution within the different Zeeman states is affected by the angle θ between a laser propagation vector, $\vec{k}$, and a magnetic field vector, $\vec{B}$.

- Returning now to FIGs. 2A-B, it is possible to associate the heading error (or at least a proportion thereof) associated with change in direction of the magnetic field, as
- 15 changing the Zeeman population distribution, which then affects the sum of the line-shapes and therefore the resonance frequency of the measurement line-shape e.g. as illustrated by different peaks **260**, **262** of FIG. 2A and zero-crossings **261**, **263** of FIG. 2B.

20 *Population distribution among different Zeeman levels*

FIGs. 4-B are a simplified schematics of Zeeman level populations, according to some embodiments of the disclosure.

A steady-state Zeeman distribution, n_{m_F} , under optical pumping by a circular polarized light may be calculated using rate equations e.g. according to feature/s of [19].

- 25 Where FIG. 4A and FIG. 4B display normalized population distribution at the different Zeeman levels of $F=4$. Where, FIG. 4A and FIG. 4B illustrate, for example, Zeeman populations for beams having different direction but the same circular polarization (e.g. first **104** and second pass **112** beams FIG. 1).

- FIGs. 5A-B are plots of resonance line-shapes for different Zeeman levels of the
- 30 $F=4$ states, according to some embodiments of the disclosure.

Where FIG. 5B illustrates an enlarged portion of FIG. 5A and all of the 9 the respective Zeeman levels $m_F=-4$ to $m_F=4$ are indicated on FIGs. 5A-B.

FIGs. 5A-B, in some embodiments, illustrate the effective line shapes for the Zeeman population distribution of FIG. 4A.

The total signal L_{tot} , (e.g. measurement signal) is theorized to be a sum of all line-shapes. Where the magnetic resonance frequency, in some embodiments, is extracted as
 5 the frequency of the maximum of L_{tot} .

FIG. 4A and FIGs. 5A-B and the x-axis position of the line shapes for the different m_f levels visible in FIGs. 5A-B detail, theoretically, background to line shape illustrations of FIGs. 2A-D.

10 *Exemplary magnetic resonance for different magnetic field directions*

FIG. 6 is a plot of magnetic resonance frequency with angle, according to some embodiments of the disclosure.

Where the dashed line plot corresponds to resonance frequency with θ_1 for a first beam with a propagation vector in a first direction and having a first direction circular
 15 polarization, θ_1 being an angle between a magnetic field and the first direction.

Where the solid line plot corresponds to resonance frequency with $-\theta_1$ for a second beam with a propagation vector in a second direction (θ_2) and having a first direction circular polarization, being an angle between a magnetic field and the second direction. Where the first direction and the second direction are opposite. FIG. 6 is produced by
 20 determining, for each line, for each different magnetic field angle, Zeeman population distribution and, from the distribution (and line-shapes for the different Zeeman levels), the total line-shape for the angle. Where the total line-shapes are used to provide a value of magnetic resonance frequency for the angle which is plotted in FIG. 6.

FIG. 6 illustrates symmetry of the two lines, addition of their values providing a
 25 uniform resonance frequency for different orientations of the magnetic field with respect to the light beams e.g. the uniformity corresponding to reduced heading error e.g. in comparison to a single pass magnetometer system.

Exemplary method

30 FIG. 7 is a method of measuring a magnetic field, according to some embodiments of the disclosure.

At **700**, in some embodiments, a vapor chamber (e.g. vapor chamber **106** FIG. 1, e.g. vapor chamber) containing alkali vapor atoms is pumped with one or more beam

circularly polarized laser light (e.g. light **104** FIG. 1), the beams herein termed “pumping” beam/s.

At **702**, in some embodiments, a circularly polarized beam of laser light is passed into the vapor chamber, the beam termed a “probe” beam. Where passage across the vapor chamber of the beam from a source side of the vapor chamber is termed a “first pass beam”.

In some embodiments, the pumping and probe beams are provided by a single beam.

At **704**, in some embodiments, light (e.g. light **108** FIG. 1) which has passed through the vapor chamber (the transmitted beam) is returned (e.g. reflected as a reflected beam) towards the vapor chamber to enter the vapor as a second pass beam (e.g. reversed in direction), whilst maintaining its helicity. Where, in some embodiments, the second pass beam has an opposite direction and a same helicity as the first pass beam.

At **706**, in some embodiments, losses to the light e.g. associated with absorption and/or scattering are compensated. For example by selectively heating a portion of alkali vapor atoms within the vapor chamber through which the second pass beam light propagates. For example, by broadening the reflected light beam (beam diameter extension) to produce the second pass beam e.g. prior to the second pass beam entering the vapor chamber.

In some embodiments, loss compensation includes gradient tuning. Where, in some embodiments, measurements of the light amplitude of the reflected light and that of the transmitted light (and/or first pass light) are used as feedback for loss compensation control. For example, where one or more temperature controller and/or light cross sectional area controller are controlled using the measurement signals. At **708**, in some embodiments, light emanating from the vapor chamber is measured. The measurement being used to determine a magnetic field at a region of space of the vapor chamber. Where, in some embodiments, measurement is by one or more optical sensor, for example, by one or more photodiode (e.g. photodiode **126** FIG. 1).

Where, in some embodiments, a measured signal (e.g. provided by a detector e.g. comprising one or more photodiode) is demodulated e.g. using a modulation signals, e.g. at the modulation frequency to provide magnetic resonance plot/s. Where a magnetic field measurement, in some embodiments, is extracted from the magnetic resonance plot/s e.g. according to one or more feature of the description of FIGs. 2A-D.

Exemplary loss compensation unit

FIG. 8A is a simplified schematic block diagram of a portion of a magnetometer system **800**, according to some embodiments of the disclosure.

5 FIG. 8B is a simplified schematic cross sectional view of a portion of a magnetometer system **800**, according to some embodiments of the disclosure.

In some embodiments, FIG. 8B illustrates a cross sectional view of portions of magnetometer system **800**, taken between A-A.

10 FIG. 8C is a cross sectional view of a portion of a retroflection unit **810**, according to some embodiments of the disclosure.

In some embodiments, magnetometer system **800** includes one or more feature as illustrated in and/or described regarding magnetometer **100** FIG. 1.

15 A laser light source unit **802** and/or a PMC **832** include one or more feature of laser light source unit **202** and PMC **132** respectively FIG. 1. Where, in some embodiments, laser light source unit **802** receives control signal/s from PMC **832**.

A vapor chamber **806** and a retroflection unit **810** include one or more feature of vapor chamber **106** and retroflection unit **110** FIG. 1 respectively. Where feature/s of light **804, 836, 812, 828** correspond to feature/s of light **104, 136, 112, 128** FIG. 1, respectively.

20 Referring now to FIG. 8C, in some embodiments, retrorefrection unit **810** includes at least two light diverting elements **889, 891** (e.g. each light diverting element including a mirror reflector or prism). Where the at least two light diverting elements have together zero relative phase retardance between S and P polarization of received light **136**. In some embodiments, one or more additional light diverting elements **893** (e.g., retrorefrection unit **810**, includes at least three light diverting elements) in order to cancel out the
25 accumulated relative phase change e.g., to maintain the relative phase between S and P polarization components.

Referring back now to FIG. 8A, in some embodiments, system **800** includes a loss compensation unit **814** including one or more temperature controller (e.g. heater), for example, one or more of a first temperature controller **820**, a second temperature
30 controller **824**, and a third temperature controller **821**. Although description hereinafter generally refers to heater/s **820, 824, 821** it should be understood that, in some embodiments, loss compensation unit **814** includes one or more cooler and/or one or more

of element/s **820**, **824**, **821** include cooling capabilities e.g. additionally or alternatively to heating capabilities.

In some embodiments, first heater **820** heats the vapor chamber **806** e.g. the entire vapor chamber. For example, by heating a surrounding of vapor chamber **806** e.g. first
5 heater **820** including room heating and/or cooling functionality. For example, by heating outer walls of the vapor chamber e.g. heater **820** including elements dispersed within the walls.

In some embodiments, second and/or third heater **824**, **821** heat (and/or cool) a different portion of a mixture **808** within vapor chamber **806** (mixture **808** including one
10 or more feature of mixture **108** FIG. 1). For example, by being disposed at a region of (e.g. heating element/s in contact with and/or heating directed at) a portion of the walls of the vapor chamber **806**. For example, referring to FIG. 8B which illustrates a cross sectional view of vapor chamber **806**, heater **824** and heater **821** are each disposed around a different portion of a circumference of the walls of vapor chamber **806**.

15 In some embodiments, loss compensation unit **814** includes all of first, second, and third temperature regulators **820**, **824**, **821**.

In some embodiments, loss compensation unit **814** includes a heater configured to heat a portion of the vapor chamber **806** and an external heater **830**.

In some embodiments, loss compensation unit **814** includes a single heater, for
20 example second heater **842**.

Referring back now to FIG. 8A, in some embodiments, one or both of heaters **820**, **824** include sensor/s **820**, **821**, **824**. In some embodiments, sensor/s include thermistor/s. In some embodiments, PMC **832** receives measurement data from one or more of sensor/s **818**, **819**, **822** and sends control signals to heater/s **820**, **821**, **824**. Where, in some
25 embodiments, PMC **832** one or more of processes the measurement data, and generates the control signals. Alternatively or additionally, to control of heater/s **820**, **821**, **822** by PMC, in some embodiments, one or more of element/s **820**, **821**, **824** include individual control circuitry for control of their respective heater/s.

Additionally or alternatively, to loss compensation via temperature control, in
30 some embodiments, loss compensation unit **814** includes a beam cross section control unit **840**. Where, in some embodiments, beam cross section is controlled in response to (e.g. based on) received measurement/s e.g. from one or more of sensors **846**, **847**. Where control, in some embodiments, is at the PCM. Where control is, in some embodiments,

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based on measurements received from sensors **846, 847**. Which sensors **846, 847** include one or more features of sensor/s **146, 147** FIG. 1, respectively.

In some embodiments, beam cross section control unit **840** includes one or more optical element configured to change a cross sectional diameter of the transmitted
5 reflected light **812**.

In some embodiments, the beam cross section control unit is configured to broaden a cross sectional area (e.g. cross section taken perpendicular to a direction of propagation of the light) of a received beam of light. For example, where control signal/s are provided to beam cross section control unit **840** by PMC **832**.

10 Now referring to FIG. 8B, which illustrates, in some embodiments, exemplary beam cross section control, where reflected light **836** is broadened by unit **840**. A cross section of second pass light **812** being larger than that of first pass light **804**. In some embodiments, beam broadening unit **840** includes one or more beam expander. For example, includes an optical expander, e.g., telescopic expander.

15

Exemplary loss compensation for a split-beam configuration

FIG. 9A is a simplified schematic of a split beam configuration magnetometer **901** system, according to some embodiments of the disclosure.

20 FIG. 9B is a cross sectional view of a portion of a magnetometer system **901**, according to some embodiments of the disclosure. In some embodiments, FIG. 9B illustrates a cross sectional view of portions of magnetometer system **901**, taken between B-B.

In some embodiments, a linear-polarized pump beam **908** (e.g. provided by a laser
25 light source **902**) is split (e.g. by a splitter **970**) into two parallel beams; a first beam **972**, and a second beam **974**. After the splitting, first beam **972** is polarized (e.g. using a retarder **976**) to right-hand circular polarization **980** and second beam **974** to left-hand circular polarization **982** e.g. by element **978** (where element **978**, for example, includes a quarter wave plate). Beams **980, 982** have different helicity. Beams **980, 982** traverse a
30 vapor cell **906** (which, in some embodiments, includes one or more feature of vapor cell **106** FIG.1).

Where, in some embodiments, each beam **980, 982** after traversing vapor cell **906**, is measured by a different detector; a first detector **984**, and a second detector **986**

respectively to provide a first and a second measurement signal respectively. Where, in some embodiments, detector/s **984, 986** include photodiodes e.g. each detector including a photodiode configured to output an electrical signal corresponding to light sensed.

In some embodiments, for example, as described regarding FIG. 1 and/or FIGs. 5 2A-D, beams **980, 982** are modulated (e.g. at laser source **904** where light **908** is modulated).

In some embodiments, outputs from detectors **984, 986** are subtracted from each other (e.g. using a differential amplifier **992** e.g. photodiodes **984, 986** and differential amplifier **992** forming a balanced photodiode). Where, in some embodiments, the 10 subtracted signal **994** is demodulated to provide magnetic resonance line-shape (e.g. a Lorentzian line-shape) from which a resonance value is extracted, for example, at PMC **932** e.g. to provide a measurement of magnetic field.

In some embodiments, system **901** is controlled e.g. to provide a balanced effect of each beam. Where, in some embodiments, one or more temperature controller **820** 15

General

As used within this document, the term “about” refers to $\pm 20\%$

The terms “comprises”, “comprising”, “includes”, “including”, “having” and their conjugates mean “including but not limited to”.

20 The term “consisting of” means “including and limited to”.

As used herein, singular forms, for example, “a”, “an” and “the” include plural references unless the context clearly dictates otherwise.

Within this application, various quantifications and/or expressions may include use of ranges. Range format should not be construed as an inflexible limitation on the 25 scope of the present disclosure. Accordingly, descriptions including ranges should be considered to have specifically disclosed all the possible subranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed subranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers 30 within the stated range and/or subrange, for example, 1, 2, 3, 4, 5, and 6. Whenever a numerical range is indicated within this document, it is meant to include any cited numeral (fractional or integral) within the indicated range.

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It is appreciated that certain features which are (e.g., for clarity) described in the context of separate embodiments, may also be provided in combination in a single embodiment. Where various features of the present disclosure, which are (e.g., for brevity) described in a context of a single embodiment, may also be provided separately
5 or in any suitable sub-combination or may be suitable for use with any other described embodiment. Features described in the context of various embodiments are not to be considered essential features of those embodiments, unless the embodiment is inoperative without those elements.

Although the present disclosure has been described in conjunction with specific
10 embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, this application intends to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

All references (e.g., publications, patents, patent applications) mentioned in this
15 specification are herein incorporated in their entirety by reference into the specification, e.g., as if each individual publication, patent, or patent application was individually indicated to be incorporated herein by reference. Citation or identification of any reference in this application should not be construed as an admission that such reference is available as prior art to the present disclosure. In addition, any priority document(s)
20 and/or documents related to this application (e.g., co-filed) are hereby incorporated herein by reference in its/their entirety.

Where section headings are used in this document, they should not be interpreted as necessarily limiting.

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CLAIMS:

1. A magnetic field strength measurement system comprising:
a vapor chamber holding alkali metal vapor;
5 a light source unit configured to supply circularly polarized laser light and positioned to feed a first pass beam of said circularly polarized light into said vapor chamber;
a retroflection unit comprising least one optical element and configured to reverse a direction, while maintaining polarization, of said first pass beam upon exit from said
10 vapor chamber to provide a second pass beam to said vapor chamber, said second pass beam having an opposite direction, and same circular polarization as said first pass beam;
a detector positioned to measure light emitted from said vapor chamber; and
circuitry configured to:
provide a modulating signal to said source, said modulating signal
15 configured to modulate said first pass beam;
receive a measurement signal from said detector;
demodulate said measurement signal using said modulating signal to provide a demodulated measurement signal; and
determine a resonance frequency from one or both of said modulating
20 signal and said demodulated measurement signal.
2. The system according to claim 1, wherein said circuitry is configured to provide said modulation signal at a plurality of modulation frequencies,
wherein said demodulated measurement signal comprises a plurality of
25 amplitudes each amplitude associated with a frequency of said plurality of modulation frequencies.
3. The system according to claim 1, wherein said circuitry is configured to extract a resonance frequency from said demodulated measurement signal.
30
4. The system according to claim 3, wherein said circuitry comprises a lock-in amplifier configured to receive said measurement signal and said modulating signal and outputting said demodulated measurement signal.

5. The system according to claim 3, wherein said demodulated measurement signal comprises a quadrature plot and where said circuitry is configured to extract a resonance frequency as a zero-crossing of a said quadrature plot.

5

6. The system according to claim 1, wherein said circuitry is configured to use said demodulated measurement signal as feedback to said modulation signal to maintain said demodulated measurement signal at a set value, where said resonance frequency is extracted as a steady state frequency of said modulation signal.

10

7. The system according to any one of claims 1-6, wherein said light source unit comprises a laser source of linearly polarized light and one or more optical element configured to convert the linearly polarized light into circularly polarized light.

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8. The system according to any one of claims 1-7, wherein said first pass beam is fed to said vapor chamber in a first direction and where said retroreflector is positioned to reverse a direction of said first pass beam to provide said second pass beam.

9. The system according to any one of claims 1-8, comprising a loss compensation unit configured to increase a resonance light signal produced by said vapor chamber and associated with said second pass beam.

10. The system according to claim 9, wherein said compensation unit comprises at least one heater configured to heat at least a portion of said alkali metal vapor through which said second pass beam passes.

11. The system according to any one of claims 9-10, wherein said loss compensation unit comprises one or more temperature controller configured to control temperature of one or more portion of said vapor chamber.

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12. The system according to any one of claims 9-11, wherein said loss compensation unit comprises one or more beam broadening element in a path of said

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second pass beam prior to entry of said second pass beam to said vapor chamber as said second pass beam.

13. The system according to any one of claims 1-12, wherein said detector
5 comprises a photodiode.

14. The system according to any one of claims 1-13, wherein said retroreflector unit comprises at least two light diverting elements.

10 15. The system according to claim 14, wherein each of said at least two light diverting element comprises a reflecting prism or a mirror.

16. The system according to any one of claims 14-15, wherein said at least two light diverting elements comprises three light diverting elements.
15

17. A method of magnetic field strength measurement comprising:
supplying a first beam of circularly polarized light and a second beam of circularly polarized light to a pumped vapor chamber holding alkali metal vapor;
measuring light emitted from said vapor chamber to provide one or more
20 measurement signal;
controlling one or more of temperature of one or more portion of said alkali metal vapor and beam cross sectional area of one or more of said first beam and said second beam.

25 18. The method according to claim 17, comprising determining a magnetic resonance frequency from said measurement signal.

19. The method according to claim 18, comprising determining the magnetic field strength using said magnetic resonance frequency.
30

20. A system of magnetic field strength measurement system comprising:
a vapor chamber holding alkali metal vapor;
a source of laser light;

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one or more optical element configured to receive said laser light and provide a first circularly polarized beam of light and a second circularly polarized beam of light to said vapor chamber;

one or more sensor configured to measure one or more of:

5 said first circularly polarized beam of light;

 said second circularly polarized beam of light;

 light emitted from said vapor chamber;

 a compensation unit comprising one or more temperature controller and one or more beam area controller;

10 a controller configured to receive one or more measurement from said one or more sensor and to provide control signals to said compensation unit.

21. A method of measuring magnetic field strength comprising:

 providing a modulating signal at a plurality of modulation frequencies;

15 directing a first pass beam of circularly polarized light into a vapor chamber of pumped alkali metal atoms in a first direction, where said first pass beam is modulated according to said modulating signal;

 reversing a direction, while maintaining polarization, of said first pass beam upon exit from said vapor chamber to provide a second pass beam to said vapor chamber, said

20 second pass beam having an opposite direction, and same circular polarization as said first pass beam;

 acquiring a measurement signal of light emitted from said vapor chamber;

 demodulating said measurement signal using said modulating signal to provide a demodulated measurement signal;

25 determining a resonance frequency from one or both of said modulating signal and said demodulated measurement signal.

22. The method according to claim 21, wherein said demodulated measurement signal comprises a plurality of amplitudes, each amplitude associated with

30 a frequency of said plurality of modulation frequencies.

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23. The method according to claim 21, wherein said determining said resonance frequency comprises extracting said resonance frequency from said demodulated measurement signal.

5 24. The method according to claim 23, wherein demodulated measurement signal comprises a quadrature plot and where said determining said resonance frequency comprises extracting a zero-crossing of a said quadrature plot.

25. The method according to claim 21, comprising using said demodulated
10 measurement signal as feedback to said modulation signal to maintain said demodulated measurement signal at a set value, where said resonance frequency is extracted as a steady state frequency of said modulation signal.

26. The method according to any one of claims 21-25, comprising
15 compensating loss to said second pass beam to increase a resonance light signal produced by said vapor chamber and associated with said second pass beam.

27. The method according to claim 26, wherein said compensating loss
20 comprises receiving a measurement from one or more sensor.

28. The method according to claim 27, wherein said compensating loss
comprises controlling a temperature, based on said measurement from one or more sensor, of at least a part of a portion of said alkali metal vapor through which said second pass beam passes.

25 29. The method according any one of claims 27-28, wherein said compensating loss comprises controlling a beam cross area of said second pass beam, based on said measurement from one or more sensor.

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