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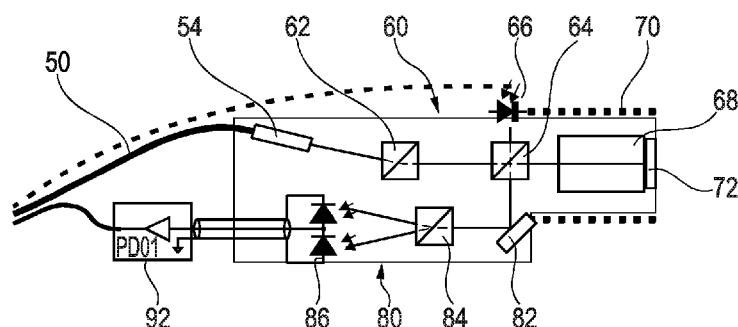


Fig. 2

(57) **Abstract:** P302170WO 32 ABSTRACT Magnetometer A sensor head for a Nonlinear Optically Pumped Magnetometer, NOPM, sensor system is 5 provided, wherein the sensor head is configured to receive a laser beam from a polarisation-maintaining optical fibre, the sensor head comprising: a polariser arranged to receive a laser beam output from the polarisation-maintaining optical fibre, the polariser for cleaning the polarisation of the received laser beam to remove orthogonally polarised light created by birefringence introduced into the polarisation-maintaining optical fibre; a non-10 polarising beam splitter arranged to receive the polarised laser beam from the polariser; a first photodetector arranged to receive a portion of the light reflected on a first pass through the non-polarising beam splitter, the first photodetector for detecting and stabilising a power of the laser beam received in the sensor head; a vapour cell for receiving polarised light of the laser beam transmitted on the first pass through the non-15 polarising beam splitter, the vapour cell containing an atomic medium that, when optically pumped with the polarised light of the laser beam nearly resonant with an atomic transition of the atoms, polarises the atoms inducing a dipole susceptible to rotation in the presence of an external magnetic field; a mirror adjacent the vapour cell and arranged to retroreflect the laser beam traversing the vapour cell back along its incident optical path to the non-20 polarising beam splitter; and a polarimeter arranged to receive the laser beam reflected on a second pass through the non-polarising beam splitter, the polarimeter for detecting a rotation of polarisation of the laser beam passing through the vapour cell due to the external magnetic field. 25

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[0001] This disclosure relates to a nonlinear optically pumped magnetometer sensor head and system thereof, a gradiometer, and a method of manufacturing the sensor head.

5 BACKGROUND

[0002] Ultrasensitive magnetometry has a number of applications in many areas such as bioscience, geophysics, non-destructive testing and evaluation, mapping anomalies in Earth's field or in numerous fundamental physics experiments. A particular area of interest is in magnetoencephalography (MEG), which is a functional neuroimaging technique for mapping brain activity, whereby ultrasensitive magnetometers may detect magnetic fields produced by electrical currents produced by the brain. Typically, superconducting quantum interference devices (SQUIDs) are used in MEG applications. SQUIDs tend to be bathed in a large liquid helium cooling unit at near 0°C, since there is low impedance at this temperature to allow SQUIDs to detect weak magnetic fields. However, this means they tend to be bulky and expensive to operate. Furthermore, SQUIDs are typically enclosed in a housing including an outer insulation padding to maintain operation at near 0°C. It can be difficult to improve sensitivity, since the insulation padding restricts how close to the test subject the SQUIDs can get.

[0003] Commercially available magnetometers vary in their performance (e.g. sensitivity, bandwidth, size, measurement direction), to meet the requirements set by applications. Among sensitive devices for measuring weak magnetic fields are Optically Pumped Magnetometers (OPMs), with sensitivities comparable to or even exceeding (SQUIDs). OPMs measure time-dependent changes in properties of light interacting with an atomic medium exposed to the magnetic field. Each OPM is based on the same three fundamental principles: (i) optical pumping of atomic spins using polarised light to create coherence between magnetic sublevels, (ii) time evolution of the spin polarisation due to the changes of the magnetic field, and (iii) optical detection of the evolved atomic spins. Whilst the polarised laser beam passes through the vapour to establish the optically pumped state, on passing therethrough the laser beam is then detected by a photodiode as a change in voltage that varies as a function of the magnetic field.

[0004] One type of OPM operates in the spin-exchange relaxation free regime (SERF) magnetometers. SERF magnetometers typically have sensitivities below 1 fT/√Hz, but can be limited in bandwidth as they can only operate in the near zero magnetic field.

[0005] Another type of OPM is a nonlinear optically pumped magnetometer (NOPM), which employs non-linear magneto-optical rotation (NMOR) by detecting the magneto-

optical-rotation of photons of a laser beam passing through a cell subject to an external magnetic field. NMOR magnetometers have a wide dynamic range and can operate in the Earth's field, but do so at the cost of lower sensitivity than SERF magnetometers. NMOR resonances observed at Larmor frequencies of $\pm 2\Omega_L$ can be used to determine the Larmor precession experienced by the vapour in the presence of external magnetic fields. As such, OPMs can be used for highly sensitive measurements to detect weak magnetic fields. The sensitivity of OPMs depends on many factors, and efforts have generally been made to increase the coherence lifetime or the number of coherent spins.

[0006] It is in this context that the present disclosure has been devised.

10 BRIEF SUMMARY OF THE DISCLOSURE

[0007] In accordance with a first aspect of the present disclosure, there is provided a sensor head for a Nonlinear Optically Pumped Magnetometer, NOPM, sensor system, wherein the sensor head is configured to receive a laser beam from a polarisation-maintaining optical fibre, the sensor head comprising: a polariser arranged to receive a laser beam output from the polarisation-maintaining optical fibre, the polariser for cleaning the polarisation of the received laser beam to remove orthogonally polarised light created by birefringence introduced into the polarisation-maintaining optical fibre; a non-polarising beam splitter arranged to receive the polarised laser beam from the polariser; a first photodetector arranged to receive a portion of the light reflected on a first pass through the non-polarising beam splitter, the first photodetector for detecting and stabilising a power of the laser beam received in the sensor head; a vapour cell for receiving polarised light of the laser beam transmitted on the first pass through the non-polarising beam splitter, the vapour cell containing an atomic medium that, when optically pumped with the polarised light of the laser beam nearly resonant with an atomic transition of the atoms, polarises the atoms inducing a dipole susceptible to rotation in the presence of an external magnetic field; a mirror adjacent the vapour cell and arranged to retroreflect the laser beam traversing the vapour cell back along its incident optical path to the non-polarising beam splitter; and a polarimeter arranged to receive the laser beam reflected on a second pass through the non-polarising beam splitter, the polarimeter for detecting a rotation of polarisation of the laser beam passing through the vapour cell due to the external magnetic field.

[0008] In doing so, the sensor head may be remotely arranged from the laser setup, thereby providing an ergonomic and practical sensor head in practice. In particular, the optics advantageously allow the optical fibre to be any desired length. The inventors have realised that in practice the light must be as polarised as possible to obtain good signal to noise ratio and ensure that the NMOR resonances observed at Larmor frequencies of

$\pm 2\Omega_L$ are accurately observed, since polarisation and power fluctuations can lead to fictitious readings (discussed in further detail below), and further the inventors have realised that optical fibres over distance can introduce birefringence. According to the disclosure however, the sensor head may be arranged remotely from the laser, since optical fibres may be several metres long. In particular, even though some birefringence may be introduced into the optical fibre over distance, the sensitivity of the sensor head may advantageously be improved by reducing polarisation and power fluctuations as the laser beam passes through the sensor. This is achieved by providing the polariser together with the polarisation-maintaining fibre and splitting the beam with one portion of the beam for being detected by the first photodetector. In particular, even though the optical fibre is polarisation-maintaining, by providing the polariser, the laser beam may be cleaned inside the sensor head after traversing the optical fibre by filtering out any orthogonal components of the beam introduced by birefringence within the optical fibre, i.e. to reduce polarisation fluctuations. Furthermore, by providing the non-polarising beam splitter together with the first photodetector, the cleaned laser beam can be split so that one of the split beams being detected by the photodetector can be used for stabilising the power of the laser beam, for example via a feedback loop, thereby tuning the laser to accommodate for power fluctuations in real time. The other of the split beams can then be used for taking measurements via the vapour cell and polarimeter. Another advantage is that the same laser beam is used for both optically pumping the atomic vapour (i.e. to induce the magnetically sensitive state in the vapour) and probing to measure the changes in the magnetic field. In doing so, the amount of power required to operate the sensor head is reduced by virtue of using a single laser beam, and also leads to improved sensitivity since the different split beams originating from the same laser beam will be in phase, thereby leading to reduced power fluctuations. Yet another advantage is that by providing the double pass through the non-polarising beam splitter, the components are advantageously arranged to provide a compact sized ergonomic sensor head that is practical in use, and can be placed very close to the test subject, giving rise to an improved signal to noise ratio. A further advantage lies in that the mirror doubles the optical path length by reflecting the laser beam to pass through the vapour cell twice, thereby increasing the rotation angle of the electric vector of the laser beam and improving the signal to noise ratio.

[0009] The polariser may be a birefringent polariser that is configured to remove the orthogonally polarised light by deflecting the orthogonally polarised light. The polariser may be a first Wollaston prism interposed between the non-polarising beam splitter and an output of the polarisation-maintaining optical fibre. The first Wollaston prism is arranged in a reverse arrangement. Placing the Wollaston prism in the reverse arrangement means that the Wollaston prism is arranged to reduce the separation angle of incident beams

when they exit the Wollaston prism rather than split incident light. The Wollaston prism may be arranged to refract the extraordinary ray (i.e. the electric vector having its polarisation along the optic axis of the laser beam) that is aligned with the slow axis to exit the Wollaston prism along a central axis. The Wollaston prism may be arranged to refract the ordinary ray (i.e. the electric vector having its polarisation perpendicular to the optic axis of the laser beam which is introduced because of the birefringence in the optical fibre) so as to be deflected away from the central axis on exiting the Wollaston prism.

[0010] By arranging the Wollaston prism in the reverse configuration, this means that when the beam is aligned on the slow axis, the Wollaston prism can efficiently filter out any light components on the fast axis introduced by birefringence within the optical fibre. In doing so, this simplifies the setup for cleaning polarisation, such that the arrangement efficiently and cost effectively cleans the laser beam. Furthermore, by directing the extraordinary ray along the central axis on exiting the Wollaston prism, this reduces the size of the sensor head by efficiently directing the beam inside the sensor head.

[0011] The sensor head may further comprise a collimator for the polarisation-maintaining optical fibre and configured to collimate the laser beam to have a 0.5 to 2 mm beam waist. The collimator may be configured to rotate around a central axis of an output of the polarisation-maintaining optical fibre.

[0012] The first photodiode may be configured to communicate with a modulator for performing at least one of amplitude modulation and frequency modulation on the laser beam. Accordingly, the power of the laser beam may be controlled in real time, based on a signal output by the first photodiode to the modulator that performs amplitude or frequency modulation on the laser beam.

[0013] The sensor head may be further configured to be arranged in parallel with another sensor head, wherein the another sensor head is a sensor head as previously described. Each sensor head may be in phase lock loop. In doing so, multiple sensor heads may be used together to improve sensitivity of the measurements.

[0014] The sensor head may further comprise a solenoid having a length and a cross-sectional area defining a volume, wherein the vapour cell is arranged within the volume defined by the solenoid. The solenoid may have a diameter in the range of 2 to 4 cm, and may be approximately 3 cm. The solenoid may have 40 to 80 turns, and may have approximately 60 turns. The solenoid may be configured to provide a uniform bias field across the vapour cell, the uniform bias field in the range of up to 50 μT , and optionally up to 1 μT , and optionally in the range of 100 to 150 nT. This arrangement helps to make the magnetic field bias uniform, so as to improve the signal to noise ratio of the readings provided by the sensor.

[0015] The solenoid may have an extending portion that extends past an end of the vapour cell by up to 1 cm, and may be in a range of 0.5 mm to 0.5 cm. In doing so, the object being measured may be placed very close to the vapour cell, and making the measurements of the width of the resonance highly sensitive.

5 [0016] The extending portion of the solenoid may have a higher concentration of coils than a remaining portion of the solenoid that surrounds the vapour cell. For example, the solenoid may have an extra 3 to 5 turns in the extending portion than the remaining portion of the solenoid. By providing extra turns in the protruding end of the solenoid, this creates a stronger magnetic field at the surface of the object being measured. For example, when
10 used as a brain scanning device, this means that the sensor head may be placed in contact with a patient's head so that the vapour cell is very close to the patient's head, thereby giving rise to improved sensitivity.

[0017] The diameter of the vapour cell may be at least 1 cm less than the diameter of the solenoid. In doing so, this improves the accuracy of the readings even when the sensor
15 itself is small, since the width of the resonance in this configuration is relatively large by using a uniform and relatively large solenoid for generating the bias field.

[0018] The sensor head may further comprise a solenoid support configured to support the solenoid.

[0019] The sensor head may be arranged to receive an end of the polarisation-
20 maintaining optical fibre, such that the polarisation-maintaining optical fibre extends into the sensor head. In doing so, the laser beam may be received inside the sensor head so as to be cleaned on being output by the laser beam, thereby helping to maintain the laser beam polarisation as intended.

[0020] A first optical path may be defined from the polariser to the non-polarising beam
25 splitter, a second optical path may be defined from the non-polarising beam splitter to the first photodetector, such that the portion of the laser beam reflected on the first pass through the non-polarising beam splitter and received by the first photodetector traverses the second optical path, and a third optical path may be defined from the non-polarising beam splitter through the vapour cell to the mirror, such that the polarised light of the laser
30 beam transmitted on the first pass through the non-polarising beam splitter received by vapour cell traverses the third optical path. The first optical path and the third optical path may be concentrically aligned with a central axis of the vapour cell. The second optical path may be substantially orthogonal to the first optical path. The second pass may transmit light received from the mirror out of the non-polarising beam splitter substantially
35 orthogonally to the third optical path. The mirror may be substantially planar, and the third optical path may have an angle of incidence that is substantially 0° with respect to the

planar surface of the mirror. Such an arrangement of optics helps to reduce the incident and reflection angle of the laser beam on the mirror, and helps to keep the direction of the magnetic field parallel to the laser beam probe, at which NMOR resonances are observed at Larmor frequencies of $\pm 2\Omega_L$. In doing so, this improves the signal to noise ratio by
5 reducing the amplitude of any non-NMOR resonances arising at other Larmor frequencies which generally occur when the angle of incidence and reflection is significant. Accordingly, this further improves the accuracy of readings.

[0021] The non-polarising beam splitter may be a 90/10 non-polarising beam splitter, such that the portion of the light reflected on the first pass through the non-polarising beam
10 splitter to traverse along the second optical path is 90% of the laser beam, and 10% of the laser beam is caused to traverse along the third optical path. In doing so, 90% of the incident power of the laser beam can be fed into the feedback loop to the modulator for monitoring the power inside the sensor, while 10% of the laser beam is transmitted into the vapour cell to take measurements. Using such a high proportion of 90% of the laser beam
15 for the feedback loop improves the power stabilisation of the sensor system. For example, the first photodetector may measure the power of the 90% of the laser beam received and send the signal to a proportional-integral-derivative (PID) controller, which in turn feeds into the modulator that modulates the laser beam input into the optical fibre. In doing so, the 90% of the laser beam detected by the photodetector effectively monitors the power
20 inside the sensor head and provides an error signal for accurately improving power stabilisation in the sensor.

[0022] The vapour cell may comprise a tube housing an atomic vapour. The atomic vapour may comprise at least one alkali atomic element. The atomic element may be selected from rubidium, caesium and potassium. The tube may include an antirelaxation
25 paraffin coating. The vapour cell may include a buffer gas. Using an antirelaxation paraffin coating and/or a buffer gas enables the sensor to work at room temperature.

[0023] The polarimeter may be configured to communicate with the modulator for performing at least one of amplitude modulation and frequency modulation on the laser beam. Alternatively, the polarimeter may be configured to communicate with a laser for
30 emitting the laser beam, the signal output by the polarimeter for modulating the current of the laser beam at the laser.

[0024] The polarimeter may be a balanced polarimeter comprising: a polarising beam splitter for receiving a light beam traversing the second pass from the non-polarising beam splitter; and a second photodetector arranged to detect at least one of the split beams
35 refracted through the polarising beam splitter. The polarimeter may comprise a third photodetector, wherein the second photodetector is arranged to detect a first of the split

beams refracted through the polarising beam splitter, wherein the third photodetector is arranged to detect a second of the split beams refracted through the polarising beam splitter, and wherein the second photodetector and the third photodetector are connected in series. The polarising beam splitter may be a second Wollaston prism inclined at an angle of approximately 45° with respect to incident light. The sensor head may further comprise another mirror arranged along the second pass and interposed between the non-polarising beam splitter and the polarising beam splitter for reflecting the light beam from the non-polarising beam splitter to the polarising beam splitter. Such an arrangement of optics provides a streamlined and ergonomic sensor head with a reduced size.

10 **[0025]** The sensor head of any one of the preceding claims, wherein the sensor head is for detecting brain signals.

[0026] In accordance with a second aspect of the present disclosure, there is provided a gradiometer comprising: a first non-polarising beam splitter arranged to receive a laser beam output from a polarisation-maintaining optical fibre; a first sensor head as previously described, wherein the first sensor head is arranged to receive one of the split laser beams from the first non-polarising beam splitter; a second sensor head as previously described, wherein the second sensor head is arranged to receive another of the split laser beams from the first non-polarising beam splitter. In other words, the gradiometer uses the same principles as the sensor head above, but with two sensor heads receiving portions of a laser beam via the first non-polarising beam splitter. Whilst the sensor head as defined in claim 1 allows for scalar measurement of magnetic fields, the gradiometer allows for measuring the gradient of the magnetic field.

[0027] The first non-polarising beam splitter may be a 50/50 non-polarising beam splitter for causing approximately 50% of the laser beam to be transmitted to the first sensor head and approximately 50% of the laser beam to be transmitted to the second sensor head. Splitting the beam equally for both sensor heads in the gradiometer means that both the NOPM sensor heads in the gradiometer advantageously cancel out common noise, thereby improving the sensitivity of the gradiometer.

[0028] In accordance with a third aspect of the present disclosure, there is provided a Nonlinear Optically Pumped Magnetometer, NOPM, sensor system comprising: a laser configured to emit a laser beam; a first modulator configured to perform at least one of amplitude modulation, AM, and frequency modulation, FM, on the laser beam emitted by the laser; a first polarisation-maintaining optical fibre having an input and an output, wherein the input of the optical fibre is arranged to receive the modulated laser beam; and a first sensor head of a type described herein arranged to receive the laser beam output by the polarisation-maintaining optical fibre.

[0029] The NOPM sensor system may further comprise a zero order half-waveplate interposed between the laser and the input of the polarisation-maintaining optical fibre, the zero order half-waveplate for polarising the laser beam emitted by the laser so as to be aligned with a slow axis of the first polarisation-maintaining optical fibre. With the first
5 Wollaston prism in the reverse arrangement, the polarisation of the laser beam may be efficiently cleaned. In particular, the laser beam is aligned on the slow axis, such that the Wollaston prism in the reverse arrangement may deflect any birefringently orthogonally introduced ray aligned on the fast axis for efficiently cleaning the laser beam.

[0030] The first modulator may be an acousto-optical modulator, AOM. The AOM is
10 configured to perform at least one of amplitude modulation, AM, and frequency modulation, FM.

[0031] The NOPM sensor system may further comprise a lock-in amplifier configured to receive a signal from the polarimeter, the lock-in amplifier for tracking a magnetic field signal measured by the first sensor head. The lock-in amplifier may be configured to output
15 a signal to the first modulator for performing AM or FM on the laser beam. Alternatively, the lock-in amplifier may be configured to output a signal to the laser for performing current modulation on the laser beam. Accordingly, the lock-in amplifier may provide a feedback loop for stabilising modulation of the amplitude and/or frequency by the modulator, or of the current by the laser.

[0032] The NOPM sensor system may further comprise a feedback loop for stabilising modulation by the first modulator based on a signal output by the first photodetector of a type described herein. The feedback loop may comprise a proportional-integral-derivative, PID, controller configured to receive the signal output by the first photodetector of a type described herein and output a signal to the first modulator for stabilising the power of the
25 laser beam by the first modulator. In doing so, this improves power stabilisation of the laser beam, by correcting for power fluctuations that may arise whilst the laser beam is traversing the optical fibre, thereby taking account of any stresses, etc. that the optical fibre may experience that may affect the polarisation of the laser beam. This is due to the signal being output by the PID into the first modulator being directly based on the signal
30 output by the first photodiode being arranged to detect the power of the laser beam before the laser beam has entered the vapour cell.

[0033] The NOPM sensor system may further comprise: a plurality of sensor heads including the first sensor head, each sensor head being arranged in parallel and being as previously defined; a plurality of polarisation-maintaining optical fibres including the first
35 polarisation-maintaining optical fibre, each polarisation-maintaining optical fibre for a corresponding sensor head from among the plurality of sensor heads; a plurality of

- modulators including the first modulator, each modulator for the corresponding sensor head; and a plurality of polarising beam splitters arranged in series with the laser for receiving the laser beam from the laser, each beam splitter for the corresponding sensor head and configured to reflect a portion of the laser beam to the corresponding sensor head via the corresponding modulator and the corresponding polarisation-maintaining optical fibre. Each modulator may be configured to perform at least one of a AM and FM on a corresponding laser beam independently from other modulators in the plurality of modulators, based on the light detected by the first photodetector of the corresponding sensor head, the plurality of modulators consisting of the at least one further modulator and the first modulator. In doing so, this reduces the size of the system whilst improving sensitivity as each portion of the laser beam may independently modulated according to the conditions of the optical fibre. In particular, each optical fibre may be experiencing different stresses, so this allows for tailored modulation according to the specific environment of the given sensor head.
- 15 **[0034]** The NOPM sensor system may further comprise at least one of a plurality of lock-in amplifiers and a plurality of PID controllers, each being for a corresponding sensor head.
- [0035]** The NOPM sensor system may further comprise: a first beam splitter interposed between the laser and the first modulator, wherein a portion of the light beam is received by the first modulator; and a spectrometer for fixing the wavelength of the laser and receiving another portion of the laser beam from the first beam splitter. The spectrometer may be used for performing saturated absorption spectroscopy for fixing the wavelength of the laser beam in real time.
- 20 **[0036]** In accordance with a fourth aspect of the present disclosure, there is provided a method of manufacturing a sensor head for a Nonlinear Optically Pumped Magnetometer, NOPM, sensor system, wherein the sensor head is configured to receive a laser beam from a polarisation-maintaining optical fibre, the method comprising: providing a polariser arranged to receive a laser beam output from the polarisation-maintaining optical fibre, the polariser for cleaning the polarisation of the received laser beam to remove orthogonally polarised light created by birefringence introduced into the polarisation maintaining fibre; providing a non-polarising beam splitter arranged to receive the polarised laser beam from the polariser; providing a first photodetector arranged to receive a portion of the light reflected on a first pass through the non-polarising beam splitter, the first photodetector for detecting and stabilising a power of the laser beam received in the sensor head; providing a vapour cell for receiving polarised light of the laser beam transmitted on the first pass through the non-polarising beam splitter, the vapour cell containing an atomic medium that, when optically pumped with the polarised light of the laser beam nearly resonant with an
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atomic transition of the atoms, polarises the atoms inducing a dipole susceptible to rotation in the presence of an external magnetic field; providing a mirror adjacent the vapour cell and arranged to retroreflect the laser beam traversing the vapour cell back along its incident optical path to the non-polarising beam splitter; and providing a polarimeter
5 arranged to receive the laser beam reflected on a second pass through the non-polarising beam splitter, the polarimeter for detecting a rotation of polarisation of the laser beam passing through the vapour cell due to the external magnetic field.

[0037] The method may further comprise providing a support for supporting the polariser, the non-polarising beam splitter, the first photodetector, the vapour cell, the mirror and the
10 polarimeter. The method may further comprise affixing the polariser and the non-polarising beam splitter to a base of the support.

BRIEF DESCRIPTION OF THE DRAWINGS

[0038] Examples of the invention are further described hereinafter with reference to the accompanying drawings, in which:

15 Fig. 1 is a schematic view of a sensor system according to a first example of the disclosure;

Fig. 2 is a schematic view of a sensor head according to the first example of the disclosure;

Fig. 3 is a perspective view of the sensor head of Fig. 2;

20 Fig. 4 is a cross-sectional top view of the sensor head of Fig. 3;

Fig. 5 shows a signal output of the voltage changing over time by a PID controller in the absence of a lock-in amplifier;

Fig. 6 shows the signal output of the voltage changing over time by the PID controller according to the first example of the disclosure;

25 Fig. 7 is a schematic view of a sensor system according to a second example of the disclosure;

Fig. 8 is a schematic view of a gradiometer according to a third example of the disclosure;

30 Fig. 9 is a flow chart of a first method of manufacturing the sensor head of the disclosure;

Fig. 10a is a schematic perspective view of a Wollaston prism refracting incident light when arranged to split an incident beam; and

Fig. 10b is a schematic perspective view of a Wollaston prism in a reverse configuration.

DETAILED DESCRIPTION

5 [0039] The present inventors have realised that there is room for improving sensitivity in detecting rotation in NOPMs, reducing complexity of the sensors and making NOPMs more compact.

10 [0040] In particular, the inventors have identified a limitation in that NOPMs measure the magnetic field changes in the direction of the propagation of the probe beam. In order to put the tested sample close to the vapour cell, the probe beam needs to be retro-reflected using a thin mirror and the tested object is placed directly behind the mirror. After passing the cell a second time, the probe beam needs to be analysed using a polarimeter comprising of polarising beam splitter and two photodiodes operating in differential mode. Therefore, the reflected beam has to be spatially separated from the incident beam without changing its polarisation as well as without increasing the size or complexity of the sensor head.

[0041] Another challenge lies in reducing the size of NMOR OPMs. Although NMOR magnetometers are intrinsically scalar (i.e. they measure the magnitude rather than direction of the field), it is still possible to extract information about the direction of the field. As discussed above, when the field to be measured is applied exactly along the probe beam propagation, the NMOR resonances are observed only at Larmor frequencies of $\pm 2\Omega_L$. Compared to SERF magnetometers, NMOR signals are small in amplitude, but with NMOR resonances being so narrow, they can accurately yield high sensitivities. However, if the field is not parallel to the probe beam, additional resonances at Larmor frequencies of $\pm\Omega_L$ appear and the amplitude of Larmor frequencies of $\pm 2\Omega_L$ resonances decreases proportionally to the angle. Therefore, the incident/reflection angle needs to be kept as small as possible, which is easy to implement on an optical table over which two beams can be sufficiently separated. However, when it comes to making a relatively small handheld sensor, it is highly impractical and one needs to compromise between sensitivity and the sensor size. Whilst a lens and manipulating the beam path may help to improve sensitivity in SERF sensors, this can complicate the sensor assembly and also increase its size. Furthermore, whilst small OPM sensors may utilise methods for improving sensitivity to directions other than the probe beam, this usually means that the cell is further from the tested object in order to accommodate for the optics, thereby reducing the amplitude of the signal.

35 [0042] Another issue is that the inhomogeneity of the bias field broadens the resonance linewidth, which in turn can reduce the sensitivity of the sensor. Whilst providing a solenoid

that is bigger and longer than the cell and wrapped around the cell may help to produce a more homogeneous bias field across the cell, doing so generally causes the size of the sensor to increase. The inventors have therefore realised the importance of improving the signal to noise ratio for acquiring useful results, whilst reducing the sensor size.

5 **[0043]** A further challenge may arise when using an optical fibre to deliver light to the sensor. To deal with the polarisation or power fluctuations, a polarisation-maintaining optical fibre may be used with the polarisation of the input beam being aligned to the slow axis of the fibre and the output polarisation cleaned using polarisation optics. Whilst an optical fibre is advantageous in creating separation between the laser and the sensor head
10 so that the laser need not be limited to the conditions where the sensor head is used, the optical fibre may suffer from temperature changes and stress, for example by being bent. Accordingly, even when the optical fibre itself is polarisation-maintaining, any stress and temperature changes risk introducing birefringence into the optical fibre, so that the fibre itself may effectively act as a half-waveplate. In doing so, the laser beam traversing the
15 optical fibre risks having orthogonal electric vectors introduced, thereby effectively unpolarising the laser beam. Since the essence of optical magnetometry lies in the detection of magneto-optical-rotation, any orthogonally introduced electric vectors can reduce the sensitivity of the NOPM signal. This is because it can be impossible to distinguish between the magneto-optical rotation or rotation resulting from induced
20 birefringence by the optical fibre. Whilst a polariser may be introduced to clean the beam, the inventors have found that polarisation fluctuations projected by the polariser risk causing power fluctuations that in practise can result in small changes in the observed Larmor frequency. In doing so, this can result in fictitious magnetic fields, thereby limiting the accuracy of the magnetometer. As such, the inventors have realised the importance of
25 maintaining polarisation of the laser beam, particularly when high sensitivity is required.

[0044] Fig. 1 shows a first example of a NOPM sensor system 10, which includes a laser 20, a modulator 40, an optical fibre 50 and a sensor head 60. The NOPM sensor system in the specific example of Fig. 1 is used in MEG for neuroimaging, such as for detecting auditory evoked brain fields. However, the disclosure is not limited to this, and the NOPM
30 sensor system may be used for measuring weak magnetic fields across a number of sectors, from bioscience, geophysics, non-destructive testing and evaluation, mapping anomalies in Earth's field and in numerous fundamental physics experiments.

[0045] The laser 20 is configured to emit a laser beam. It will be understood that any suitable laser may be used. In the specific example of Fig. 1, a single laser beam is output
35 by the laser 20. A beam splitter 22 is arranged ahead of the laser such that the laser beam passes therethrough. The beam splitter 22 may be of any suitable type, such as a

polarising beam splitting cube interposed between two waveplates 24, which splits the laser beam into two. Alternatively, a non-polarising beam splitter may be used. In particular, it will be understood that the beam splitter may reflect to divert a portion of the laser beam, while the remaining portion of the laser beam continues on its same trajectory without diversion. The two waveplates 24 may be zero-order half-waveplates.

[0046] In the first example, the system 10 includes a spectrometer 26. In the specific example of Fig. 1, the spectrometer 26 is a saturated absorption spectroscopy for fixing and tuning the wavelength of the laser. As shown in Fig. 1, the spectrometer 26 includes a waveplate 28 (such as a zero-order half-waveplate), a beam splitter 30, a vapour cell 32, a second waveplate 34 (such as a zero-order quarter-waveplate), a mirror 36 and a photodiode 38. As shown in Fig. 1, one of the split beams produced by the beam splitter 22 is diverted to the spectrometer 26, so as to pass through the first waveplate 28 and fall incident on the beam splitter 30 on a first pass therethrough, which splits the incident laser beam. The vapour cell 32 is arranged to receive a portion of the laser beam reflected by the beam splitter 30. The vapour cell 32 may include any suitable vapour, such as an alkali gas e.g. rubidium. The laser beam then passes through the second waveplate 34 and is reflected by the mirror 32 back along its incident optical path for a second pass through the vapour cell 32 and the beam splitter 30. The photodiode 38 is arranged to detect the laser beam along its second pass through the beam splitter 30, whereby its readings can be used to tune the wavelength of the laser beam in real-time according to the atomic transition frequency of the atomic vapour. It will however be understood that whilst a saturated absorption spectroscopy has been described here in relation to the specific example of Fig. 1, any suitable spectrometer may be implemented.

[0047] Turning now to the modulator 40, whilst the beam splitter 22 diverts a portion of the laser beam to the spectrometer 26, the modulator 40 is arranged to receive the remaining portion of the laser beam that passes through the beam splitter 22 via another beam splitter 44, as shown in Fig. 1. The beam splitter 44 may be a polarising beam splitter arranged to reflect light toward the modulator 40. In the first example, the modulator 40 is an acousto-optical modulator (AOM) configured to perform at least one of amplitude modulation, AM, and frequency modulation, FM, on the laser beam. However, the disclosure is not limited to this and the modulator may be any suitable modulator for performing at least one of AM and FM. The modulation is performed based on readings from the sensor head via a feedback loop, which is described in detail further below.

[0048] As shown in Fig. 1, after making a first pass through the modulator 40, the laser beam passes through a quarter waveplate 46 and falls incident on a mirror 48, which reflects the laser beam on a second pass through the modulator 40 and transmitted back

through the beam splitter 44 to the optical fibre 50. As shown in Fig. 1, one or more mirrors 49 may be arranged to reflect the laser beam from the beam splitter 44 to the optical fibre 50. In doing so, the optical path for the laser beam can be tailored to the environment as required.

5 **[0049]** The optical fibre 50 is a polarisation-maintaining optical fibre, so as to help maintain the polarisation of the laser beam as it traverses therethrough. The input of the optical fibre 50 is arranged to receive the laser beam, whilst the output of the optical fibre 50 is coupled with the sensor head 60, as shown in Fig. 1. In the first example, the optical fibre 50 has a length of up to 10 m, but it will be understood that the optical fibre may be
10 tailored according to the environment. Providing such a long optical fibre means that the sensor head 60 advantageously need not be limited to being proximal to the laser 20, thereby giving more freedom for setup spanning different areas, for example in a different room.

[0050] In the first example of the disclosure, before being fed into the optical fibre 50, the
15 laser beam passes through another half-waveplate 52, which is arranged proximal and opposite the input of the optical fibre 50. The half waveplate 52 may be a zero-order half-waveplate. The half-waveplate 52 is arranged to align the polarised laser beam with the slow axis on entering the optical fibre 50.

[0051] In the first example of the disclosure, the sensor system includes a collimator 54
20 arranged at the output of the optical fibre 50, whereby the collimator 54 is for collimating the laser beam to have a beam waist of approximately 1 mm, but may be in the range of 0.5 to 2 mm beam waist. In the first example of the disclosure, the collimator 54 is a pigtailed gradient-index (GRIN) lens glass collimator. However, it will be understood that the collimator may be of any suitable type. Furthermore, in some examples of the
25 disclosure, another collimator may be provided at the input of the optical fibre 50. In the first example of the disclosure, the collimator 54 is advantageously rotated around its axis to cause the laser beam to be output with a high power. In doing so, this reduces the need for a further half waveplate, and helps to achieve approximately a $1:10^5$ extension ratio of the unwanted photons with orthogonal polarisation.

30 **[0052]** The sensor head 60 is shown in more detail in Figs. 2 to 4, where Fig. 2 shows a schematic view of the sensor head for illustrative purposes, while Figs. 3 and 4 show perspective and top views respectively of the sensor head 60. The sensor head 60 includes a polariser 62, a non-polarising beam splitter 64, a photodetector 66, a vapour cell 68, a mirror 72, and a polarimeter 80.

35 **[0053]** The output of the optical fibre 50 is disposed inside the sensor head 60. Arranged proximal in front of the output of the optical fibre 50 is the polariser 62 arranged to clean

the polarisation of the laser beam on entry into the sensor head 60. The polariser 62 is a birefringent polariser. In the first example of the disclosure, the polariser 62 is a Wollaston prism, which is typically substantially cubic and includes two triangular calcite prisms with orthogonal crystal axes that are cemented together, whereby its internal interface causes an unpolarized beam to split into two polarized rays that diverge at an angle of between approximately 15° to 45° . In the first example of the disclosure, the Wollaston prism is arranged in the reverse configuration, so that the Wollaston prism is arranged to reduce the separation angle of incident beams when they exit the Wollaston prism rather than split incident light. For illustration purposes, Fig. 10a shows a Wollaston prism when used for splitting an incident beam, whilst Fig. 10b shows a Wollaston prism in the reverse configuration. As can be seen from Fig. 10b, when arranged in the reversed configuration, the Wollaston prism reduces the separation angle of two incident beams on exiting the Wollaston prism.

[0054] As discussed above, on entry into the optical fibre 50, the laser beam is aligned with the slow axis, but there is a risk that despite the optical fibre 50 being polarisation-maintaining, stresses and temperature changes can introduce birefringence into the optical fibre 50. In other words, whilst the laser beam is ideally polarised on entry into the optical fibre 50 having an extraordinary E ray aligned on the slow axis, the optical fibre 50 may introduce ordinary O rays, thereby effectively unpolarising the laser beam. Providing the Wollaston prism 62 however advantageously cleans the laser beam by filtering out the O rays introduced by birefringence. The optical fibre 50 is particularly arranged to direct the laser beam at the split angle of the E-ray, such that the E-ray on being refracted through the Wollaston prism is aligned with a central axis of the Wollaston prism, thereby directing polarised light down an optimised optical path through the sensor head. In particular, since the Wollaston prism is in the reverse arrangement, the O rays aligned on the fast axis are refracted away from the central axis of the Wollaston prism, causing them to deflect away, thereby providing a highly polarised laser beam inside the sensor head. It will of course be understood that any type of suitable polariser for filtering O rays out of the laser beam may be used instead of the Wollaston prism of the first example of the disclosure.

[0055] The non-polarising beam splitter 64 is arranged proximal to the polariser 62 to receive the polarised light of the laser beam (i.e. the cleaned laser beam) from the polariser 62, as shown in Fig. 2. In the specific example shown in Fig. 2, the non-polarising beam splitter is a 90/10 beam splitter splitting the laser beam such that 90% is reflected, while 10% is transmitted therethrough. For illustrative purposes, a first optical path is defined from the polariser 62 to the non-polarising beam splitter 64. The beam splitter 64 causes 90% of the laser beam to be reflected down a second optical path, whilst 10% is

not reflected and continues down a third optical path that is linearly aligned with the incident first optical path into the non-polarising beam splitter 64.

[0056] The photodetector 66 is arranged proximal the beam splitter 64 on the second optical path so as to receive the 90% reflected portion of the laser beam. In other words, the second optical path is defined from the non-polarising beam splitter 64 to the photodetector 66. The photodetector 66 may be of any suitable type, such as a photodiode. As can be seen from Fig. 2, the second optical path is substantially orthogonal to the first optical path. This advantageously means that the photodetector 66 may be arranged toward the side of the sensor head 60, so that the components are arranged in a manner allowing the size of the sensor head 60 to be efficiently reduced. The photodetector 66 is for use in the feedback loop, which as discussed above, is used by the modulator 40 to modulate the laser beam. In the first example of the disclosure, the NOPM sensor system includes a proportional-integral-derivative (PID) controller 42, whereby the readings of the photodetector 66 are fed into the PID controller 42, as shown in Fig. 1. The PID controller 42 may be of any suitable type. Based on the readings of the photodetector 66, the PID controller 42 determines power fluctuations occurring in real-time and outputs a signal to a voltage controlled attenuator (VVA) (not shown) which controls the modulator 40. Accordingly, the modulation may be improved, since the modulator 40 can stabilise the power of the laser beam based on the readings output by the photodetector 66, by correcting for power fluctuations that may arise whilst the laser beam is traversing the optical fibre 50, thereby taking account of any stresses, etc. the optical fibre 50 may experience that may affect the polarisation of the laser beam. Furthermore, to reduce the risk of the magnetometer following the input noise associated with the readings by the photodetector 66, the PID controller 42 is set so the feedback is fast enough to follow slow (10s and longer) changes associated with power fluctuations, but at the same time slow enough to omit fast (less than 100ms) changes associated with noise of the electronics. Moreover, by basing the modulation on such a large proportion (90%) of the polarised light of the laser beam, this gives rise to improved power and polarisation stabilisation of the laser beam in practice, by accurately measuring the polarised laser beam shortly after exiting the optical fibre 50. In the first example of the disclosure, the NOPM sensor system also includes a low-pass filter (not shown) interposed between the photodetector 66 and the PID controller 42, whereby the low-pass filter outputs a DC signal to the PID controller 42, thereby improving power stability of the system.

[0057] Turning now to the remaining portion of the laser beam on its first pass through the non-polarising beam splitter 64, as discussed above 10% of the polarised light of the laser beam is transmitted through the non-polarising beam splitter 64 on a first pass

therethrough to traverse the third optical path. The vapour cell 68 is arranged along the third optical path to receive the light on the first pass. The vapour cell 68 houses an atomic vapour. The atomic vapour may include one of or a mix of atomic elements, such as rubidium, caesium and potassium. However, any alkali atomic element may be suitable.

5 The vapour cell 68 itself may be of any suitable structure, such as substantially cylindrically-shaped or tubular. In the first example of the disclosure, the vapour cell 68 is coated with an antirelaxation paraffin coating, which advantageously allows the sensor to operate at room temperature. However, the disclosure is not limited to this and in other examples of the disclosure, the vapour cell may include a buffer gas either instead of or in
10 addition to the use of the antirelaxation paraffin coating to achieve the same effect. The buffer gas may be any suitable inert or non-flammable gas that adds pressure to the vapour.

[0058] In the first example of the disclosure, the sensor head 60 further includes a solenoid 70 that surrounds the vapour cell 68, as shown in Fig. 2. The solenoid 70 has a
15 length and a cross-sectional area that defines a volume, whereby the vapour cell is arranged within that volume. In the specific example of Fig. 2, the vapour cell 68 has a diameter of approximately 1.8 cm and a length of approximately 2 cm, while the solenoid 70 has a diameter of approximately 3 cm and has approximately 60 turns. However, the sensor head 60 is not limited to this, and the solenoid 70 may have a diameter in the range
20 of 2 to 4 cm and may have in the range of 40 to 80 turns. Furthermore, the vapour cell 68 may have a diameter of up to 2 cm and may be at least 1 cm less than the diameter of the solenoid 70. The solenoid 70 in the first example of the disclosure is supported by a support so as to suspend it around the vapour cell 68. Any suitable structural support may be implemented to do so. By providing the vapour cell 68 as being surrounded by the
25 solenoid 70, this improves the accuracy of the readings even when the sensor itself is small, since the width of the resonance in this configuration is relatively large by using a uniform and relatively large solenoid for generating the bias field.

[0059] The solenoid 70 preferably provides a uniform bias field across the vapour cell, whereby the uniform bias field is up to 50 μT , but may be up to 1 μT , and more particularly
30 in the range of 100 to 150 nT. This arrangement helps to maintain the magnetic field uniform, so as to improve the signal to noise ratio of the readings provided by the sensor.

[0060] In the first example of the disclosure, the solenoid 70 includes an extending portion that extends past an end of the vapour cell by up to 1 cm, and may be in a range of 0.5 mm to 0.5 cm. More particularly, in the specific example of Fig. 2, the solenoid 70
35 extends past both a rear and a front of the vapour cell 68, whereby the solenoid 70 extends past the rear of the vapour cell 68 (facing toward the non-polarising beam splitter

64) by approximately 1 to 10 mm, and the solenoid 70 extends past the front of the vapour cell (and over the mirror 72) by up to 1 cm, and may be as small as approximately 1 mm. Due to the solenoid 70 extending past the front end of the vapour cell 68 by such a short distance, the object being measured may be placed very close to the vapour cell, thereby improving sensitivity of the sensor readings. Moreover, this configuration of the solenoid 70 tightly wound around the vapour cell 68 helps to make the measurements of the width of the resonance highly sensitive to within 1 Hz. Furthermore, the extending portion of the solenoid 70 extending past the front end of the vapour cell 68 in the first example of the disclosure includes a higher concentration of coils than a remaining portion of the solenoid that surrounds the vapour cell. In other words, the coils arranged in the extending portion may be more densely configured than in the remaining portion. For example, the solenoid may have an extra 3 to 5 turns in the extending portion than the remaining portion of the solenoid 70. By providing extra turns in the protruding end of the solenoid, this creates a stronger magnetic field at the surface of the object being measured. For example, when used in MEG as a brain scanning device, this means that the sensor head may be placed in contact with a patient's head so that the vapour cell is very close to the patient's head, thereby giving rise to improved sensitivity.

[0061] Turning now to the mirror 72 of the sensor head 60, the mirror 72 is arranged at the end of the vapour cell 68, such that the laser beam traversing the third optical path from the non-polarising beam splitter 64 through the vapour cell 68 falls incident on the mirror 72. The third optical path is thus defined from the non-polarising beam splitter 64 through the vapour cell 68 to the mirror 72. The mirror 72 is particularly arranged in the extending portion of the solenoid 70 up front of the vapour cell 68. The mirror 72 is substantially planar and has a thickness of up to 5 mm, and may be less than 2 mm, and may be equal to or greater than 0.5 mm.

[0062] The polariser 62 and the non-polarising beam splitter 64 are arranged to project the laser beam in line with a central axis of the vapour cell 68, so that the laser beam has an angle of incidence that is substantially 0° with respect to the planar surface of the mirror 72. In other words, the first and third optical paths are concentrically aligned, whereby the polariser 62 and the non-polarising beam splitter 64 are arranged linearly with the mirror 72 as shown in Fig. 2. In the first example of the disclosure, this is achieved using the collimator 54, which is fixed at the angle matching the divergence angle of the polariser 62, so that on passing through the polariser 62, the laser beam is concentric with a central axis of the vapour cell 68. Accordingly, the mirror 72 reflects the laser beam back through the vapour cell 68 to the non-polarising beam splitter 64. In other words, the laser beam is reflected to reverse back along the same incident path (third optical path) along a second

pass through the non-polarising beam splitter 64. Providing the mirror 72 in this way advantageously doubles the optical path length by reflecting the laser beam to pass through the vapour cell 68 twice, thereby increasing the rotation angle of the electric vector of the laser beam as compared with a single pass through the vapour cell. In doing so, the sensitivity to the magnetic field may be advantageously improved. Importantly, such an arrangement of optics helps to reduce the incident and reflection angle of the laser beam on the mirror, and helps to keep the direction of the magnetic field parallel to the laser beam probe, at which NMOR resonances are observed at Larmor frequencies of $\pm 2\Omega_L$. In doing so, this improves the signal to noise ratio by reducing the amplitude of any non-NMOR resonances arising at other Larmor frequencies which generally occur when the angle of incidence and reflection is significant. Accordingly, this further improves the accuracy of readings.

[0063] During the second pass through the non-polarising beam splitter 64, the laser beam is again split to cause 90% of the laser beam to be reflected along a fourth optical path, while 10% of the laser beam is transmitted through the non-polarising beam splitter 64. The 10% of the laser beam transmitted through the non-polarising beam splitter 64 is effectively directed back toward the polariser for being deflected, whilst the remaining 90% of the laser beam is reflected toward the polarimeter 80.

[0064] In the first example of the disclosure, a mirror 82 is arranged along the fourth optical path to the side of the non-biasing beam splitter 64 to reflect the laser beam to the polarimeter 80. The fourth optical path in this case is defined from the non-polarising beam splitter 64 to the mirror 82. As can be seen from Fig. 2, the fourth optical path is orthogonal to the first and third optical paths and opposite the second optical path. Of course, it will be understood that any suitable non-orthogonal reflection angle may however be used. In the specific example of Fig. 2, the mirror 82 has an angle of incidence of approximately 45° to cause the reflected light to be arranged substantially parallel to the first optical path. Providing the mirror 82 in this way means that the polarimeter 80 may be arranged to streamline the sensor head 60, by reducing its width and size as compared to an absence of the mirror 82. Of course, it will be understood that the mirror 82 may be provided as one or more mirrors for providing a tailored optical path for reflecting the laser beam from the non-polarising beam splitter 64 to the polarimeter 80.

[0065] The polarimeter 80 is a balanced polarimeter that includes a polarising beam splitter 84 for receiving a light beam traversing the second pass from the non-polarising beam splitter 64. In the first example of the disclosure, the polarising beam splitter 84 is another Wollaston prism arranged to split an incident beam as shown in Fig. 10a, although it will be understood that any suitable polarising beam splitter may be used. As shown in

Fig. 2, the polarimeter 80 includes two photodetectors 86 arranged in series to detect the portions of the laser beam refracted through the polarising beam splitter 84. The photodetectors 86 may be of any suitable type, such as photodiodes. By detecting both portions of the laser beam that has been split by the polarising beam splitter 84, the photodetectors 86 thus accurately measure the proportion of the electric vector of the laser beam that has been rotated by external magnetic fields, as changes in voltage. However, the disclosure is not limited to this arrangement, and a single photodetector may be arranged to detect both portions of the laser beam split by the polarising beam splitter 84.

[0066] In the first example, the system 10 further includes a lock-in amplifier 90 connected to the photodetectors 86 via for example a potentiometer 92, as shown in Figs. 1 and 2. The lock in amplifier 90 may be of any suitable type. The photodetectors 86 thus output their readings to the lock-in amplifier 90, which processes and tracks the magnetic field in real time. In the first example of the disclosure shown in Fig. 1, the lock-in amplifier 90 is connected to the modulator 40 so as to output readings to the modulator 40. In doing so, the modulator 40 modulates the frequency and/or the amplitude of the laser beam based not only on the PID controller 42, but also based on the lock-in amplifier 90, in order to accurately calibrate the polarisation in real time.

[0067] In other examples of the disclosure however, the lock-in amplifier 90 may instead output its readings to the laser 20 itself rather than the modulator 40. In doing so, the lock-in amplifier 90 may perform current modulation of the laser beam directly from the source, by outputting readings to the laser 20, such that the laser beam may be controlled in real time based on the readings from the polarimeter.

[0068] When used for modulating the current, amplitude or frequency of the laser beam by either the modulator or the laser, the lock-in amplifier 90 thus also contributes to the feedback loop for stabilising the laser beam. This is particularly illustrated in Figs. 5 and 6, which show the signal output by the PID controller 42 in the absence and presence of the lock-in amplifier 90, respectively, and particularly how the voltage changes over time when no object is being measured. In particular, as can be seen from Fig. 5, when the system is not in phase lock loop (i.e. in the absence of the lock-in amplifier 90), the signal varies even though no object is being measured. Unfortunately, this can cause the magnetometer to view the signal as fictitious magnetic fields, thereby giving rise to reduced signal to noise ratio. By contrast, Fig. 6 shows that using the lock-in amplifier 90 to lock the pulse base by controlling the power of the laser beam causes the PID controller 42 to output a steady signal. In the specific example of Fig. 6, the PID signal is fixed at approximately 348 mV. Accordingly, the PID controller 42 and the lock-in amplifier 90 may together

advantageously improve the signal to noise ratio and thus the sensitivity of the sensor by maintaining a relatively constant power passing through the vapour cell 68.

[0069] Fig. 7 shows a second example of the disclosure of an NOPM sensor system 100, which may be used in the same context as the NOPM sensor system 10 of the first

5 example of disclosure, whereby multiple sensor heads 160, each having a corresponding optical fibre 150, modulator 140, lock-in amplifier 190 and PID controller 142, are connected in parallel with a laser 120. Each sensor head 160, optical fibre 150, modulator 140, lock-in amplifier 190, laser 120 and PID controller 142 may be provided as in the first example of the embodiment, as described in relation to Figs. 1 to 4. Providing multiple
10 sensor heads may allow for multiple readings to be taken simultaneously for measuring an object with a relatively large surface area.

[0070] In the second example of the disclosure, each modulator 140 is configured to perform either amplitude modulation or frequency modulation on a corresponding laser beam independently from other modulators in the plurality of modulators, based on the
15 light detected by the first photodetector of the corresponding sensor head. In doing so, this reduces the size of the system whilst improving sensitivity as each portion of the laser beam may independently modulated according to the conditions of the optical fibre. In particular, each optical fibre 150 may be experiencing different stresses according to its own environment, so this allows for tailored modulation according to the specific
20 environment of the given sensor head.

[0071] In the second example of the disclosure, the NOPM sensor system 100 further includes a spectrometer 126, whereby the spectrometer 126 is arranged in parallel with each of the sensor heads 160 and corresponding modulators 140. The spectrometer 126 may be as described in relation to the first example of the disclosure. In order to arrange
25 the spectrometer 126 and the sensor heads 160 with corresponding components, the system 100 includes a plurality of beam splitters 200 arranged in series with the laser 120 for receiving a laser beam emitted from the laser 120. The beam splitters 200 are arranged to reflect a portion of the incident laser beam toward a corresponding component selected from the spectrometer 126 and one from among the plurality of modulators 140.

30 Accordingly, a single laser beam may advantageously both pump and probe across a plurality of sensor heads.

[0072] In the second example of the disclosure, the beam splitters 200 are polarising beam splitters, with a plurality of zero-order half waveplates 210, each alternating between the laser 120 and each of the beam splitters 200. Accordingly, the polarisation of the laser
35 beam may be aligned with the desired axis before being input into each modulator 140, thereby improving the quality of the polarisation throughout the system. However, the

disclosure is not limited to this arrangement and a non-polarising beam splitter may alternatively be implemented.

[0073] Fig. 8 shows a synthetic gradiometer 300 according to a third example of the disclosure. Unlike the magnetometers 10, 100 described in relation to the first and second examples of the disclosure, the gradiometer 300 measures the gradient in the magnetic field, rather than the scalar field. The gradiometer 300 however is built on the same principles as the sensor heads 60, 160 of the first and second examples, and may be implemented in the system 10 shown in Fig. 1 by replacing the sensor head 60.

Specifically, the gradiometer 300 includes a non-polarising beam splitter 322 and two sensor heads 360, 361, whereby the sensor heads 360, 361 are as previously described. The gradiometer 300 is arranged to receive the output of an optical fibre 350, which is as previously described. The beam splitter 322 is arranged to receive a laser beam having traversed the optical fibre 350. The beam splitter 322 in the third example of the disclosure is a 50/50 beam splitter arranged to split the laser beam into equal portions. More particularly, as shown in Fig. 8, the beam splitter 322 is arranged to reflect 50% of the laser beam toward the first sensor head 360, whilst the remaining 50% is transmitted through the beam splitter 322 toward the second sensor head 361. Splitting the beam equally for both sensor heads 360, 361 in the gradiometer 300 means that common noise may be advantageously cancelled out, thereby improving the sensitivity of the gradiometer 300. As shown in Fig. 8, a mirror 323 is arranged to reflect the portion of the laser beam reflected out of the beam splitter 322 toward the first sensor head 360. In doing so, the two sensor heads 360, 361 may be arranged linearly with one another so as to provide a streamlined and sensitive gradiometer 300 that is ergonomic to use.

[0074] Fig. 9 shows a method of manufacturing a sensor head of any one of the first, second and third examples of the disclosure. In particular, the method comprises step 410 of providing a polariser arranged to receive a laser beam output from an optical fibre. Step 420 includes providing a non-polarising beam splitter arranged to receive the polarised laser beam from the polariser. Step 430 includes providing a photodetector arranged to receive a portion of the light reflected on a first pass through the non-polarising beam splitter. Step 440 includes providing a vapour cell for receiving polarised light of the laser beam transmitted on the first pass through the non-polarising beam splitter. Step 450 includes providing a mirror adjacent the vapour cell and arranged to retroreflect the laser beam traversing the vapour cell back along its incident optical path to the non-polarising beam splitter. Step 460 includes providing a polarimeter arranged to receive a the laser beam reflected on a second pass through the non-polarising beam splitter. The polariser, non-polarising beam splitter, photodetector, vapour cell, mirror and polarimeter may be as

previously described in relation to the first example of the disclosure. The method may further include providing a support for supporting the polariser, the non-polarising beam splitter, the first photodetector, the vapour cell, the mirror and the polarimeter. In such cases, the method may also include affixing the polariser and the non-polarising beam splitter to a base of the support.

[0075] There is provided a sensor head (60) for a Nonlinear Optically Pumped Magnetometer, NOPM, sensor system (10), wherein the sensor head is configured to receive a laser beam from a polarisation-maintaining optical fibre (50), the sensor head comprising: a polariser (62) arranged to receive a laser beam output from the polarisation-maintaining optical fibre, the polariser for cleaning the polarisation of the received laser beam to remove orthogonally polarised light created by birefringence introduced into the polarisation-maintaining optical fibre; a non-polarising beam splitter (64) arranged to receive the polarised laser beam from the polariser; a first photodetector (66) arranged to receive a portion of the light reflected on a first pass through the non-polarising beam splitter, the first photodetector for detecting and stabilising a power of the laser beam received in the sensor head; a vapour cell (68) for receiving polarised light of the laser beam transmitted on the first pass through the non-polarising beam splitter, the vapour cell containing an atomic medium that, when optically pumped with the polarised light of the laser beam nearly resonant with an atomic transition of the atoms, polarises the atoms inducing a dipole susceptible to rotation in the presence of an external magnetic field; a mirror (72) adjacent the vapour cell and arranged to retroreflect the laser beam traversing the vapour cell back along its incident optical path to the non-polarising beam splitter; and a polarimeter (80) arranged to receive the laser beam reflected on a second pass through the non-polarising beam splitter, the polarimeter for detecting a rotation of polarisation of the laser beam passing through the vapour cell due to the external magnetic field.

[0076] Throughout the description and claims of this specification, the words “comprise” and “contain” and variations of them mean “including but not limited to”, and they are not intended to (and do not) exclude other additives, components, integers or steps. Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

[0077] Features, integers, characteristics or compounds described in conjunction with a particular aspect, embodiment or example of the invention are to be understood to be applicable to any other aspect, embodiment or example described herein unless incompatible therewith. All of the features disclosed in this specification (including any

accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive. The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

[0078] The reader's attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

CLAIMS

1. A sensor head for a Nonlinear Optically Pumped Magnetometer, NOPM, sensor system, wherein the sensor head is configured to receive a laser beam from a polarisation-maintaining optical fibre, the sensor head comprising:
- 5 a polariser arranged to receive a laser beam output from the polarisation-maintaining optical fibre, the polariser for cleaning the polarisation of the received laser beam to remove orthogonally polarised light created by birefringence introduced into the polarisation-maintaining optical fibre;
- 10 a non-polarising beam splitter arranged to receive the polarised laser beam from the polariser;
- a first photodetector arranged to receive a portion of the light reflected on a first pass through the non-polarising beam splitter, the first photodetector for detecting and stabilising a power of the laser beam received in the sensor head;
- 15 a vapour cell for receiving polarised light of the laser beam transmitted on the first pass through the non-polarising beam splitter, the vapour cell containing an atomic medium that, when optically pumped with the polarised light of the laser beam nearly resonant with an atomic transition of the atoms, polarises the atoms inducing a dipole susceptible to rotation in the presence of an external magnetic field;
- 20 a mirror adjacent the vapour cell and arranged to retroreflect the laser beam traversing the vapour cell back along its incident optical path to the non-polarising beam splitter; and
- a polarimeter arranged to receive the laser beam reflected on a second pass through the non-polarising beam splitter, the polarimeter for detecting a rotation of polarisation of the laser beam passing through the vapour cell due to the external magnetic field.
- 25
2. The sensor head of claim 1, wherein the polariser is a birefringent polariser that is configured to remove the orthogonally polarised light by deflecting the orthogonally polarised light.
- 30 3. The sensor head of claim 2, wherein the polariser is a first Wollaston prism interposed between the non-polarising beam splitter and an output of the polarisation-maintaining optical fibre.
4. The sensor head of claim 3, wherein the first Wollaston prism is arranged in a reverse arrangement.

5. The sensor head of any one of the preceding claims, further comprising a collimator for the polarisation-maintaining optical fibre and configured to collimate the laser beam to have a 0.5 to 2 mm beam waist.
6. The sensor head of claim 5, wherein the collimator is configured to rotate around a central axis of an output of the polarisation-maintaining optical fibre.
7. The sensor head of any one of the preceding claims, wherein the first photodiode is configured to communicate with a modulator for performing at least one of amplitude modulation and frequency modulation on the laser beam.
8. The sensor head of any one of the preceding claims, further configured to be arranged in parallel with another sensor head, wherein the another sensor head is a sensor head as defined in any one of the preceding claims.
9. The sensor head of any one of the preceding claims, further comprising a solenoid having a length and a cross-sectional area defining a volume, wherein the vapour cell is arranged within the volume defined by the solenoid.
10. The sensor head of claim 9, wherein the solenoid is configured to provide a uniform bias field across the vapour cell, the uniform bias field in the range of up to 50 μT , and optionally up to 1 μT , and optionally in the range of 100 to 150 nT.
11. The sensor head of claim 9 or claim 10, wherein the solenoid has an extending portion that extends past an end of the vapour cell by up to 1 cm.
12. The sensor head of claim 11, wherein the extending portion of the solenoid has a higher concentration of coils than a remaining portion of the solenoid that surrounds the vapour cell.
13. The sensor head of any one of claims 9 to 12, wherein the diameter of the vapour cell is at least 1 cm less than the diameter of the solenoid.
14. The sensor head of any one of claims 9 to 13, further comprising a solenoid support configured to support the solenoid.
15. The sensor head of any one of the preceding claims, wherein the sensor head is arranged to receive an end of the polarisation-maintaining optical fibre, such that the polarisation-maintaining optical fibre extends into the sensor head.
16. The sensor head of any one of the preceding claims, wherein:
- a first optical path is defined from the polariser to the non-polarising beam splitter,
 - a second optical path is defined from the non-polarising beam splitter to the first photodetector, such that the portion of the laser beam reflected on the first pass through

the non-polarising beam splitter and received by the first photodetector traverses the second optical path, and

5 a third optical path is defined from the non-polarising beam splitter through the vapour cell to the mirror, such that the polarised light of the laser beam transmitted on the first pass through the non-polarising beam splitter received by vapour cell traverses the third optical path.

17. The sensor head of claim 16, wherein the first optical path and the third optical path are concentrically aligned with a central axis of the vapour cell.

10 18. The sensor head of claim 17, wherein the second optical path is substantially orthogonal to the first optical path.

19. The sensor head of any one of claims 16 to 18, wherein the second pass transmits light received from the mirror out of the non-polarising beam splitter substantially orthogonally to the third optical path.

15 20. The sensor head of any one of claims 16 to 19, wherein the mirror is substantially planar, and wherein the third optical path has an angle of incidence that is substantially 0° with respect to the planar surface of the mirror.

21. The sensor head of any one of claims 16 to 20, wherein the non-polarising beam splitter is a 90/10 non-polarising beam splitter, such that the portion of the light reflected on the first pass through the non-polarising beam splitter to traverse along the second optical path is 90% of the laser beam, and 10% of the laser beam is caused to traverse along the third optical path.

22. The sensor head of any one of the preceding claims, wherein the vapour cell comprises a tube housing an atomic vapour.

25 23. The sensor head of claim 22, wherein the tube includes an antirelaxation paraffin coating.

24. The sensor head of claim 22, wherein the vapour cell includes a buffer gas.

25. The polarimeter of any one of the preceding claims, wherein the polarimeter is configured to communicate with the modulator for performing at least one of amplitude modulation and frequency modulation on the laser beam.

30 26. The polarimeter of any one of claims 21 to 24, wherein the polarimeter is configured to communicate with a laser for emitting the laser beam, the signal output by the polarimeter for modulating the current of the laser beam at the laser.

27. The sensor head of any one of the preceding claims, wherein the polarimeter is a balanced polarimeter comprising:

a polarising beam splitter for receiving a light beam traversing the second pass from the non-polarising beam splitter; and

5 a second photodetector arranged to detect at least one of the split beams refracted through the polarising beam splitter.

28. The sensor head of claim 27, wherein the polarimeter comprises a third photodetector, wherein the second photodetector is arranged to detect a first of the split beams refracted through the polarising beam splitter, wherein the third photodetector is
10 arranged to detect a second of the split beams refracted through the polarising beam splitter, and wherein the second photodetector and the third photodetector are connected in series.

29. The sensor head of claim 27 or claim 28, wherein the polarising beam splitter is a second Wollaston prism inclined at an angle of approximately 45° with respect to incident
15 light.

30. The sensor head of any one of claims 27 to 29, further comprising another mirror arranged along the second pass and interposed between the non-polarising beam splitter and the polarising beam splitter for reflecting the light beam from the non-polarising beam splitter to the polarising beam splitter.

20 31. The sensor head of any one of the preceding claims, wherein the sensor head is for detecting brain signals.

32. A gradiometer comprising:

a first non-polarising beam splitter arranged to receive a laser beam output from a polarisation-maintaining optical fibre;

25 a first sensor head as defined in claim 1, wherein the first sensor head is arranged to receive one of the split laser beams from the first non-polarising beam splitter;

a second sensor head as defined in claim 1, wherein the second sensor head is arranged to receive another of the split laser beams from the first non-polarising beam splitter.

30 33. The gradiometer of claim 32, wherein the first non-polarising beam splitter is a 50/50 non-polarising beam splitter for causing approximately 50% of the laser beam to be transmitted to the first sensor head and approximately 50% of the laser beam to be transmitted to the second sensor head.

34. A Nonlinear Optically Pumped Magnetometer, NOPM, sensor system comprising:
a laser configured to emit a laser beam;
a first modulator configured to perform at least one of amplitude modulation, AM, and frequency modulation, FM, on the laser beam emitted by the laser;
- 5 a first polarisation-maintaining optical fibre having an input and an output, wherein the input of the optical fibre is arranged to receive the modulated laser beam; and
a first sensor head as defined in any one of claims 1 to 30 arranged to receive the laser beam output by the polarisation-maintaining optical fibre.
35. The NOPM sensor system of claim 34, further comprising a zero order half-waveplate interposed between the laser and the input of the polarisation-maintaining optical fibre, the zero order half-waveplate for polarising the laser beam emitted by the laser so as to be aligned with a slow axis of the first polarisation-maintaining optical fibre.
- 10 36. The NOPM sensor system of claim 34 or claim 35, wherein the first modulator is an acousto-optical modulator, AOM.
- 15 37. The NOPM sensor system of any one of claims 34 to 36, further comprising a lock-in amplifier configured to receive a signal from the polarimeter, the lock-in amplifier for tracking a magnetic field signal measured by the first sensor head.
38. The NOPM sensor system of claim 37, wherein the lock-in amplifier is configured to output a signal to the first modulator for performing AM or FM on the laser beam.
- 20 39. The NOPM sensor system of claim 37, wherein the lock-in amplifier is configured to output a signal to the laser for performing current modulation on the laser beam.
40. The NOPM sensor system of any one of claims 34 to 39, further comprising a feedback loop for stabilising modulation by the first modulator based on a signal output by the first photodetector of claim 1.
- 25 41. The NOPM sensor system of claim 40, wherein the feedback loop comprises a proportional-integral-derivative, PID, controller configured to receive the signal output by the first photodetector of claim 1 and output a signal to the first modulator for stabilising the power of the laser beam by the first modulator.
42. The NOPM sensor system of any one of claims 34 to 41, further comprising:
30 a plurality of sensor heads including the first sensor head, each sensor head being arranged in parallel and being as defined in any one of claims 1 to 29;

a plurality of polarisation-maintaining optical fibres including the first polarisation-maintaining optical fibre, each polarisation-maintaining optical fibre for a corresponding sensor head from among the plurality of sensor heads;

5 a plurality of modulators including the first modulator, each modulator for the corresponding sensor head; and

a plurality of polarising beam splitters arranged in series with the laser for receiving the laser beam from the laser, each beam splitter for the corresponding sensor head and configured to reflect a portion of the laser beam to the corresponding sensor head via the corresponding modulator and the corresponding polarisation-maintaining optical fibre.

10

43. The NOPM sensor system of claim 42, wherein each modulator is configured to perform at least one of AM and FM on a corresponding laser beam independently from other modulators in the plurality of modulators, based on the light detected by the first photodetector of the corresponding sensor head, the plurality of modulators consisting of the at least one further modulator and the first modulator.

15

44. The NOPM sensor system of claim 42 or claim 43, further comprising at least one of a plurality of lock-in amplifiers and a plurality of PID controllers, each being for a corresponding sensor head.

45. The NOPM sensor system of any one of claims 34 to 44, further comprising:

20 a first beam splitter interposed between the laser and the first modulator, wherein a portion of the light beam is received by the first modulator; and

a spectrometer for fixing the wavelength of the laser and receiving another portion of the laser beam from the first beam splitter.

46. A method of manufacturing a sensor head for a Nonlinear Optically Pumped Magnetometer, NOPM, sensor system, wherein the sensor head is configured to receive a laser beam from a polarisation-maintaining optical fibre, the method comprising:

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providing a polariser arranged to receive a laser beam output from the polarisation-maintaining optical fibre, the polariser for cleaning the polarisation of the received laser beam to remove orthogonally polarised light created by birefringence introduced into the polarisation maintaining fibre;

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providing a non-polarising beam splitter arranged to receive the polarised laser beam from the polariser;

providing a first photodetector arranged to receive a portion of the light reflected on a first pass through the non-polarising beam splitter, the first photodetector for detecting and stabilising a power of the laser beam received in the sensor head;

5 providing a vapour cell for receiving polarised light of the laser beam transmitted on the first pass through the non-polarising beam splitter, the vapour cell containing an atomic medium that, when optically pumped with the polarised light of the laser beam nearly resonant with an atomic transition of the atoms, polarises the atoms inducing a dipole susceptible to rotation in the presence of an external magnetic field;

10 providing a mirror adjacent the vapour cell and arranged to retroreflect the laser beam traversing the vapour cell back along its incident optical path to the non-polarising beam splitter; and

providing a polarimeter arranged to receive the laser beam reflected on a second pass through the non-polarising beam splitter, the polarimeter for detecting a rotation of polarisation of the laser beam passing through the vapour cell due to the external magnetic field.

47. The method of claim 46, further comprising providing a support for supporting the polariser, the non-polarising beam splitter, the first photodetector, the vapour cell, the mirror and the polarimeter.

48. The method of claim 47, further comprising affixing the polariser and the non-polarising beam splitter to a base of the support.

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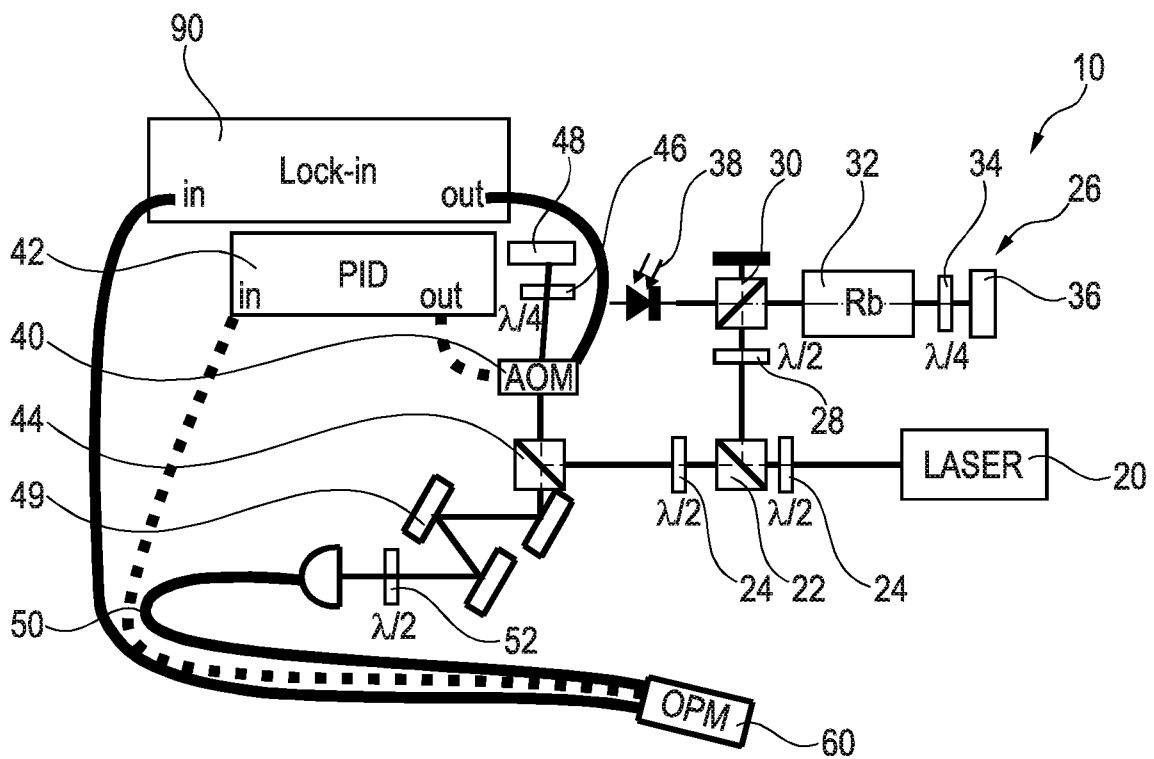


Fig. 1

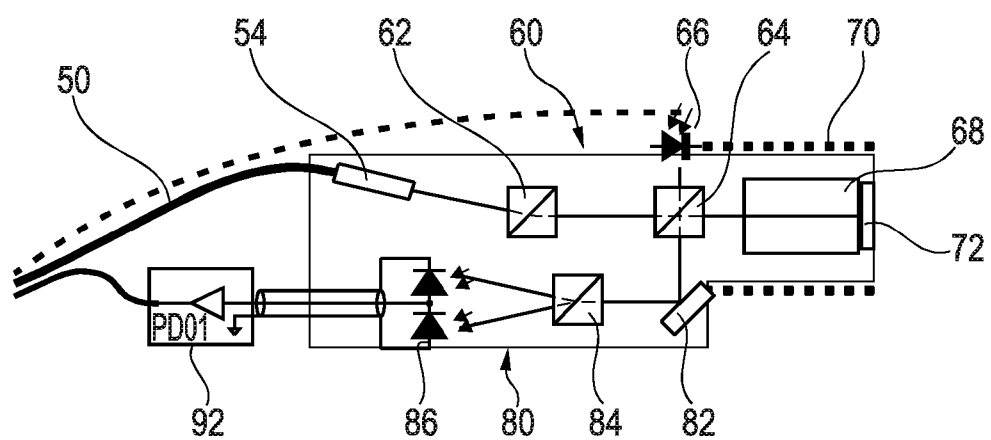


Fig. 2

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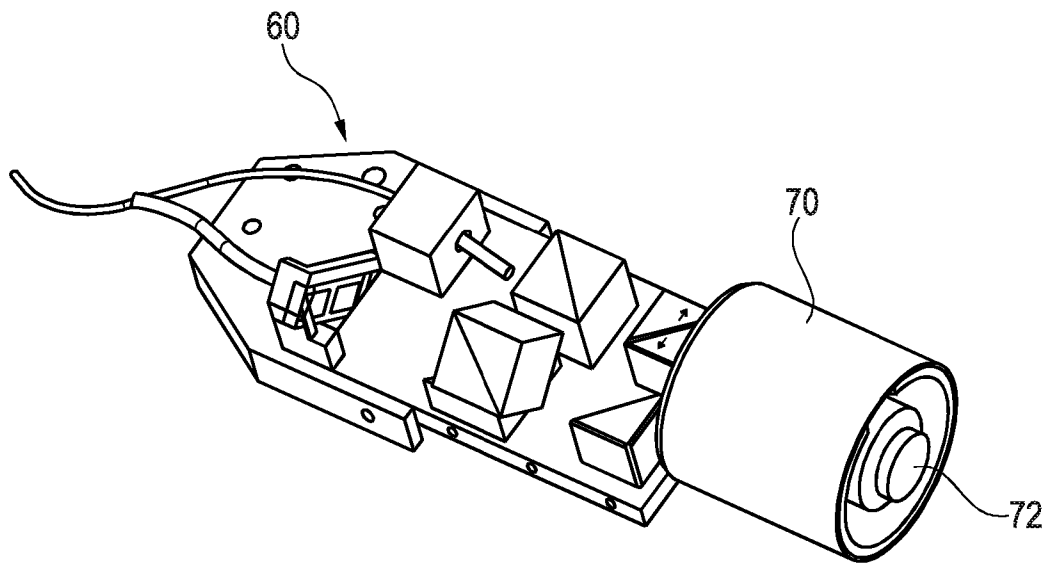


Fig. 3

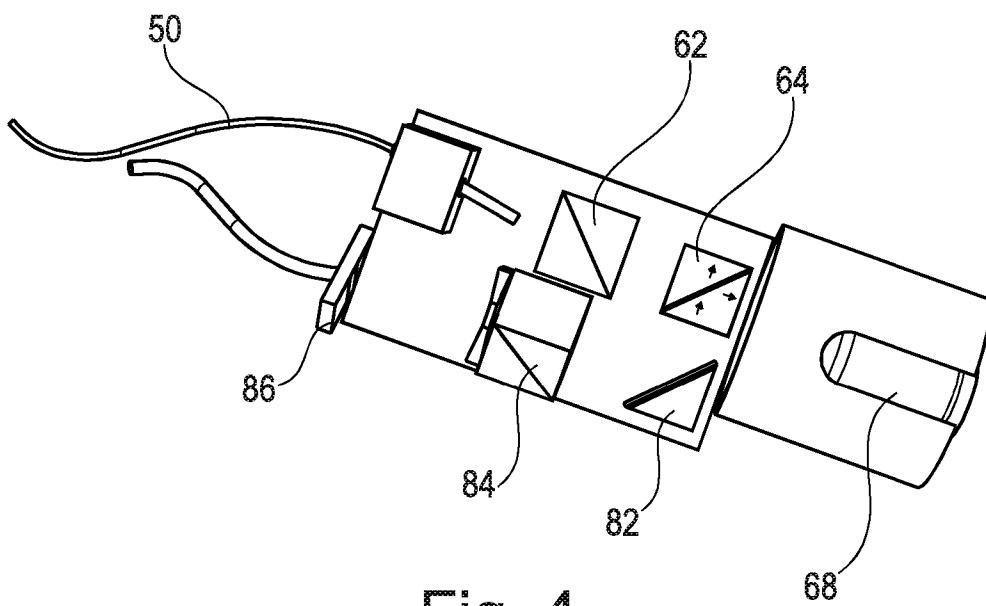


Fig. 4

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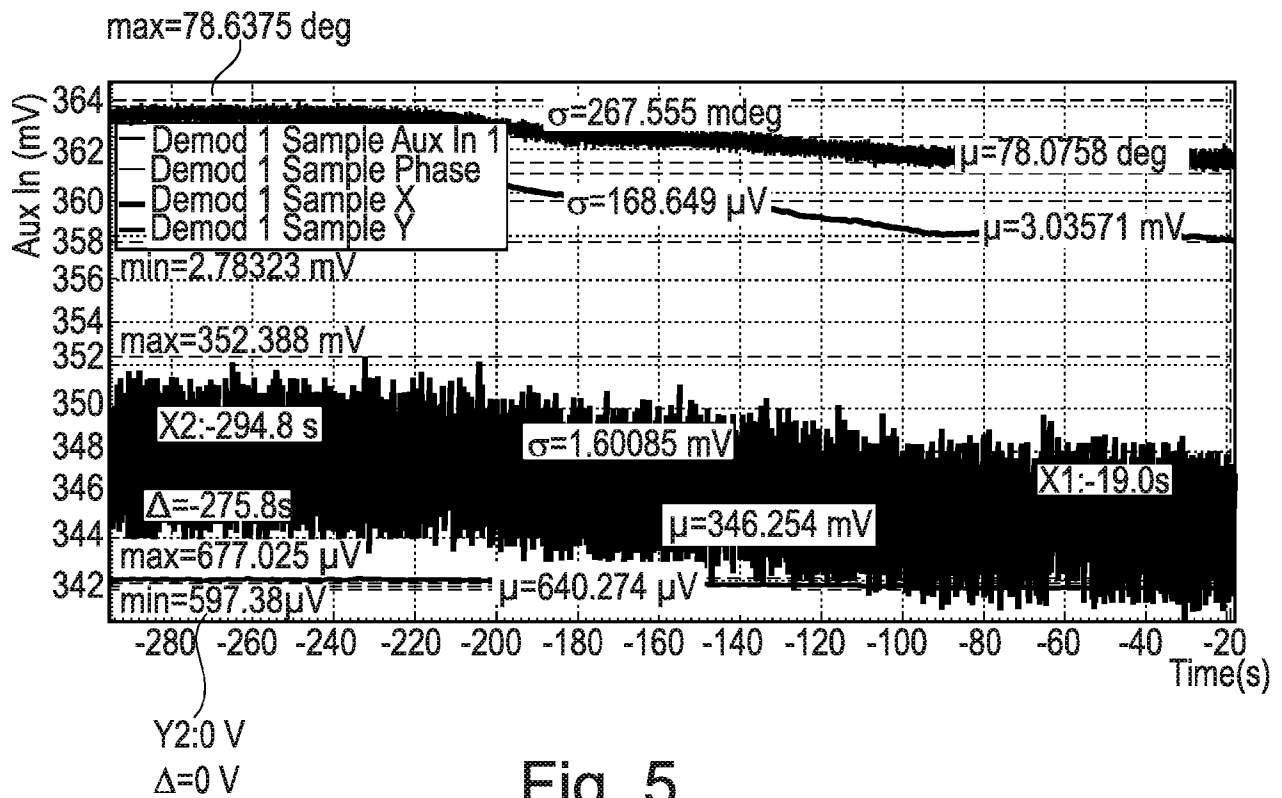


Fig. 5

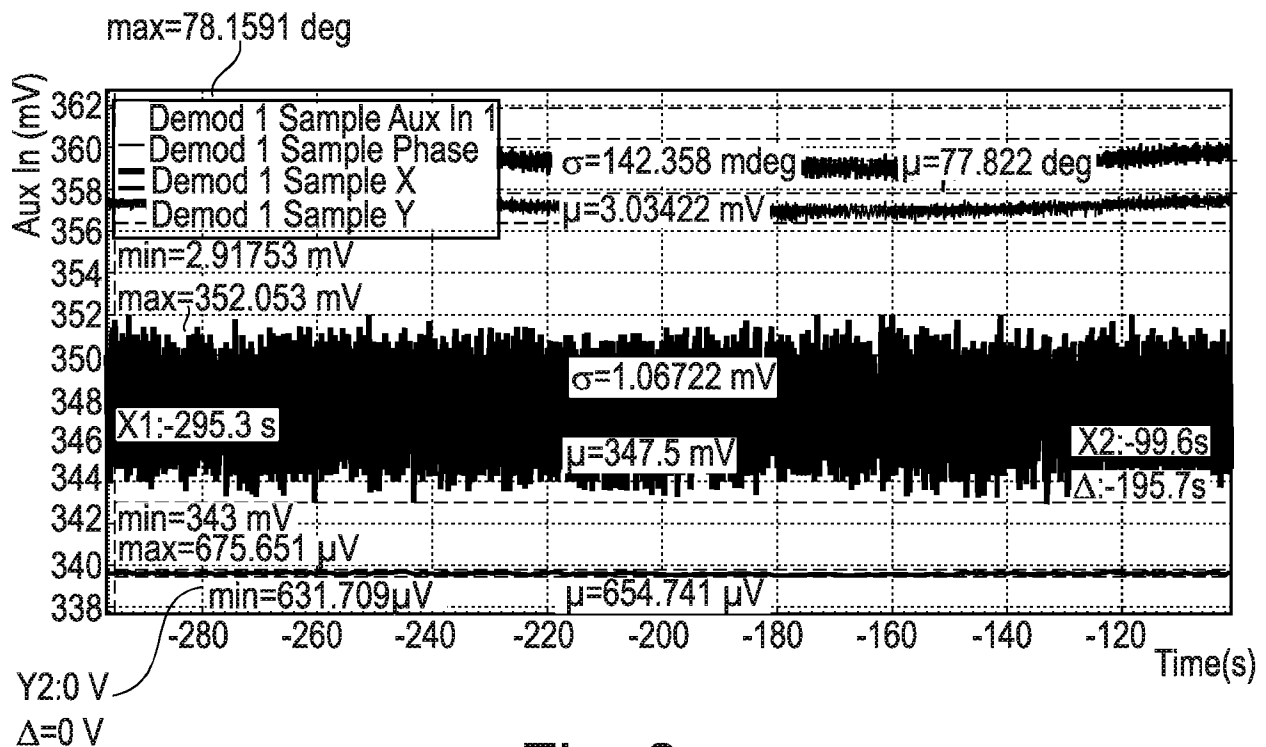


Fig. 6

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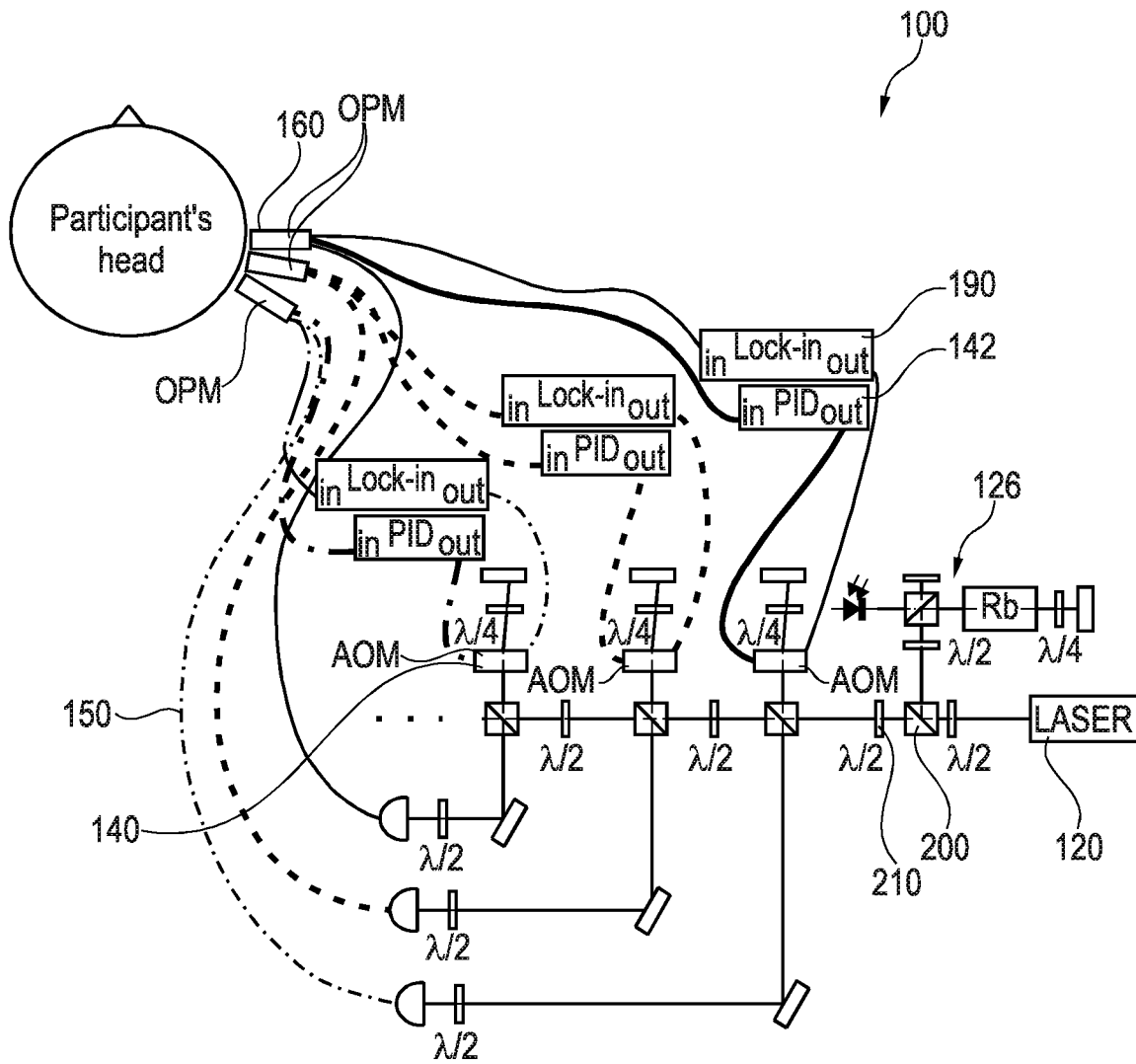
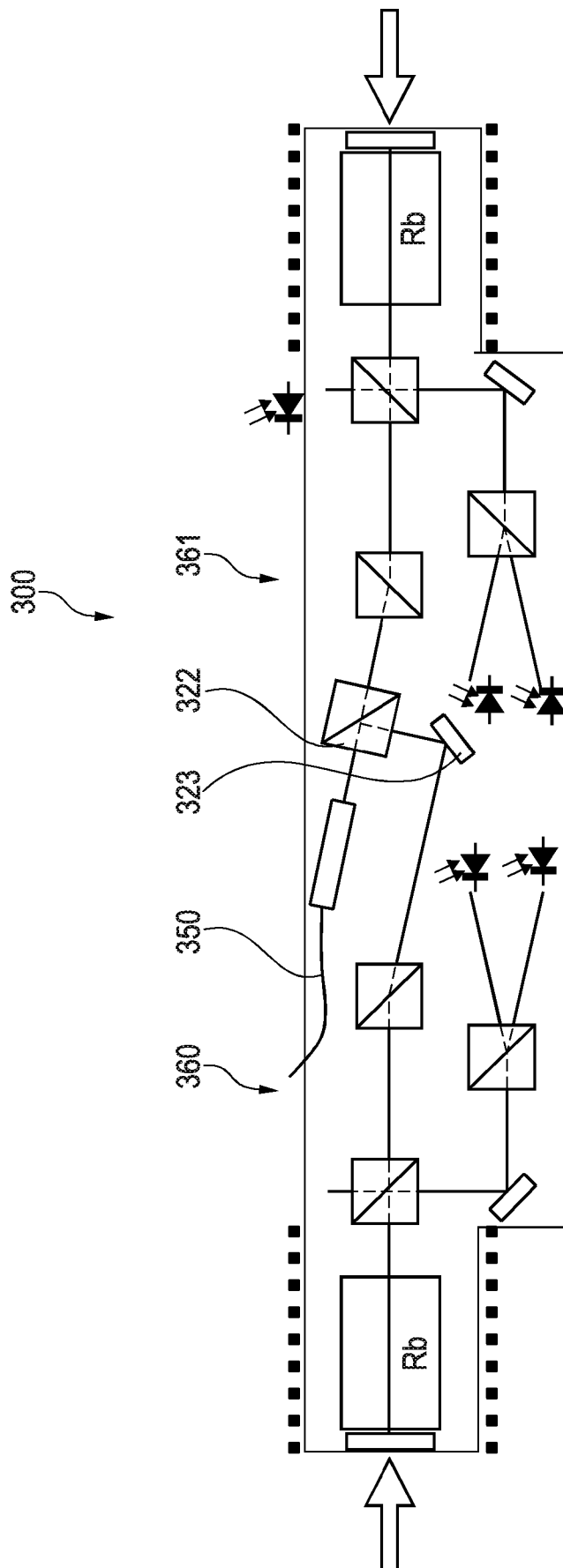


Fig. 7

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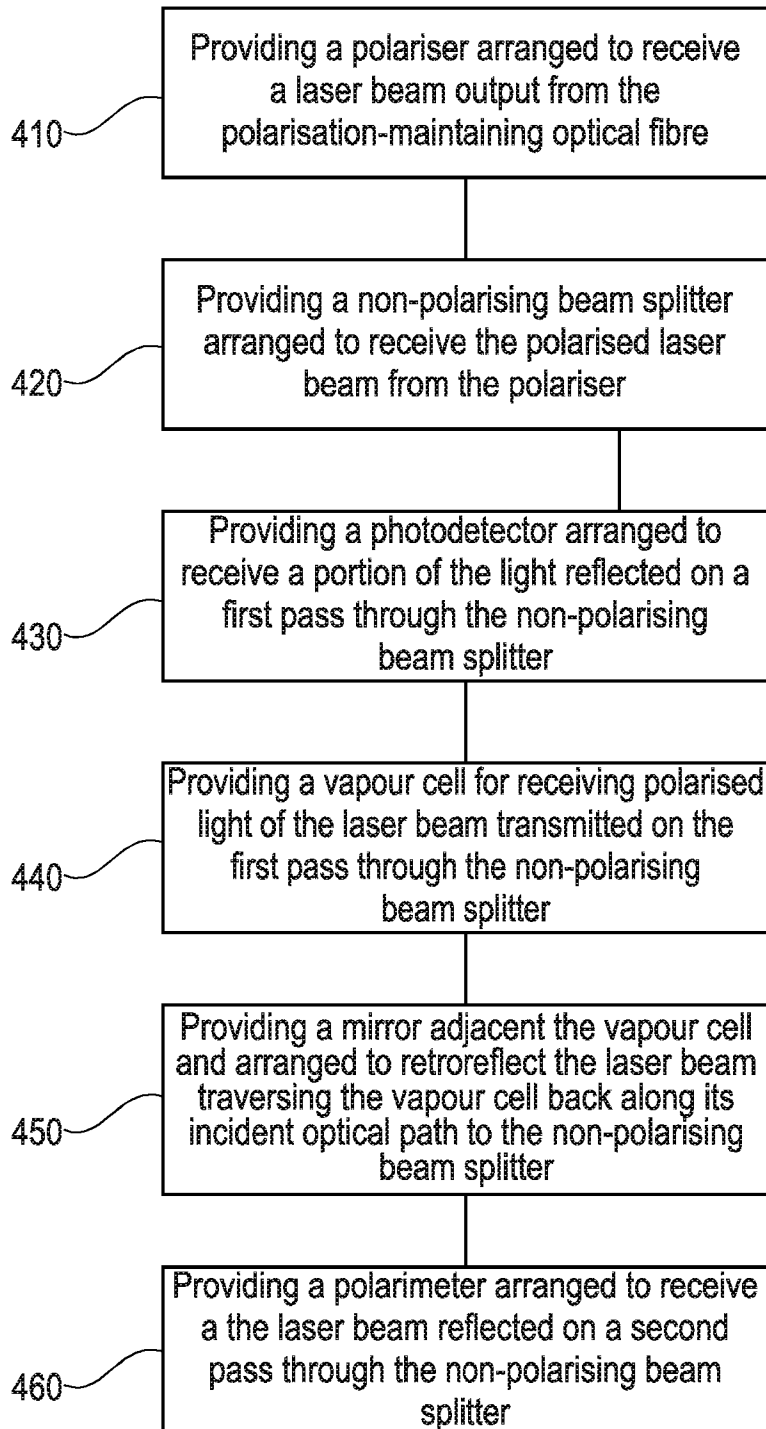


Fig. 9

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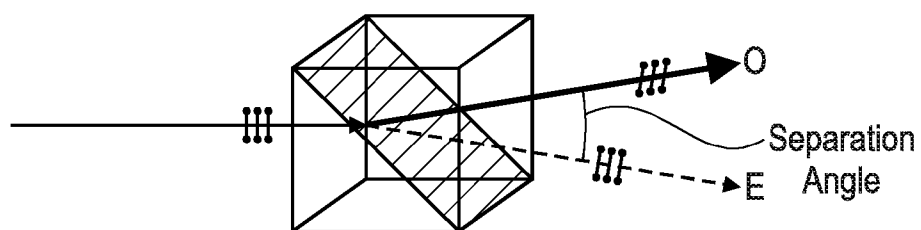


Fig. 10a

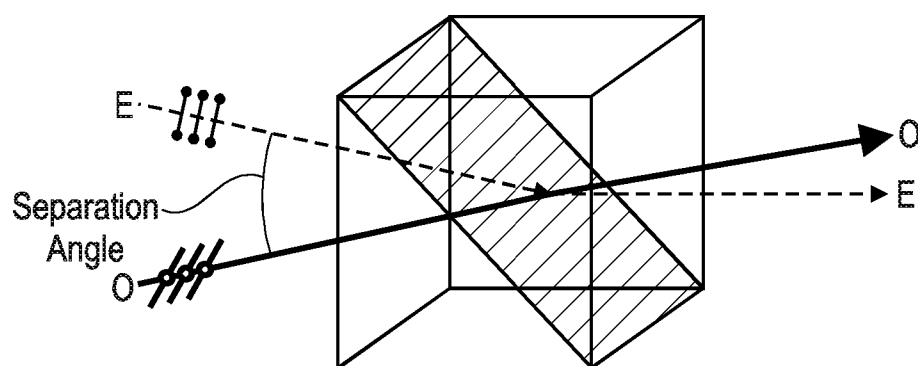


Fig. 10b

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2021/052755

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01R33/26

ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01R

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

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

EPO-Internal, BIOSIS, COMPENDEX, EMBASE, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2012 159427 A (SEIKO EPSON CORP)	25, 26
A	23 August 2012 (2012-08-23)	
	the whole document	1-24, 27-48

X	PERRY A R ET AL: "An all-optical atomic gradiometer with sub-20 fT/cm/sqrtm Hz sensitivity in a 22 muT earth-scale magnetic field",	25, 26
	ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853,	
A	30 August 2020 (2020-08-30), XP081751625, figure 1	1, 32, 34, 46

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Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search

18 January 2022

Date of mailing of the international search report

25/01/2022

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INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2021/052755

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATTON B ET AL: "A remotely interrogated all-optical Rb magnetometer", APPLIED PHYSICS LETTERS, AMERICAN INSTITUTE OF PHYSICS, 2 HUNTINGTON QUADRANGLE, MELVILLE, NY 11747, vol. 101, no. 8, 20 August 2012 (2012-08-20), pages 83502-83502, XP012164874, ISSN: 0003-6951, DOI: 10.1063/1.4747206 [retrieved on 2012-08-21]	25,26
A	figure 1	1,34,46
A	FAN WENFENG ET AL: "Analysis on the Magnetic Field Response for Nuclear Spin Co-Magnetometer Operated in Spin-Exchange Relaxation-Free Regime", IEEE ACCESS, vol. 7, 28 February 2019 (2019-02-28), pages 28574-28580, XP011715206, DOI: 10.1109/ACCESS.2019.2902181 [retrieved on 2019-03-15] figure 1	1,34,46
A	KIM YOUNG JIN ET AL: "Highly sensitive multi-channel atomic magnetometer", 2018 IEEE SENSORS APPLICATIONS SYMPOSIUM (SAS), IEEE, 12 March 2018 (2018-03-12), pages 1-4, XP033345770, DOI: 10.1109/SAS.2018.8336715 [retrieved on 2018-04-11] figure 1a	1,34,46
A	NARDELLI N. V. ET AL: "A conformal array of microfabricated optically-pumped first-order gradiometers for magnetoencephalography", EPJ QUANTUM TECHNOLOGY, [Online] vol. 7, no. 1, 11 September 2020 (2020-09-11), XP055879856, ISSN: 2662-4400, DOI: 10.1140/epjqt/s40507-020-00086-4 Retrieved from the Internet: URL:https://link.springer.com/article/10.1140/epjqt/s40507-020-00086-4/fulltext.html > [retrieved on 2022-01-17] figure 1	1,32,34,46

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2021/052755

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CORT JOHNSON ET AL: "A two-color pump probe atomic magnetometer for magnetoencephalography", FREQUENCY CONTROL SYMPOSIUM (FCS), 2010 IEEE INTERNATIONAL, IEEE, PISCATAWAY, NJ, USA, 1 June 2010 (2010-06-01), pages 371-375, XP031738498, ISBN: 978-1-4244-6399-2 figure 1 -----	1, 34, 46
A	ANTHONY P. COLOMBO ET AL: "Four-channel optically pumped atomic magnetometer for magnetoencephalography", OPTICS EXPRESS, vol. 24, no. 14, 29 June 2016 (2016-06-29), page 15403, XP055375418, DOI: 10.1364/OE.24.015403 figure 1a -----	1, 34, 36

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2021/052755

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2012159427 A	23-08-2012	JP 5682344 B2	11-03-2015
		JP 2012159427 A	23-08-2012
