TITLE:

A MAGNETOMETER SYSTEM AND METHOD

TECHNOLOGICAL FIELD

The present invention is in the field of magnetometers, and particularly relates to atomic magnetometers and techniques for high accuracy magnetic field measurements thereby.

BACKGROUND

Atomic magnetometers (hereinafter also referred to as vapor-cell based magnetometers or magnetic sensors) are widely used in various applications where accurate magnetic field measurements are required. Atomic magnetometers detect an external magnetic field by measuring the coherent precession frequency of atomic spins about the external magnetic field (the measurement is conducted on a vapor cell containing vapor of atomic elements whose spins are measured). Conventionally, two main kinds of atomic magnetometers are used for realizing the coherent precession of atomic spins: radio-optical magnetometers (which apply a radio-frequency magnetic field to excite the atomic magnetic dipole transition, and thereby create the transverse spin component with respect to the external magnetic field direction), and *all-optic* vapor cell magnetometers (which are typically operable with the Bell-Bloom magnetometer setup and use modulated light of typically circular polarization (pumping) to excite the atomic magnetic dipole transition). Compared with the radio-optical magnetometer, the all-optical (Bell–Bloom) magnetometer does not need to produce the radio-frequency magnetic field and is generally capable of providing more accurate/sensitive magnetic measurements, since interference with the additional RF magnetic field is avoided.

Atomic magnetometers/sensors generally include: a vapor cell (typically a glass tubing) enclosing a certain predetermined substance composition (typically including a certain population of vaporized Alkali-like atoms and buffer gasses), a source of a pumping field (optical field or electronic/RF field) which is applied to the vapor cell to

excite vaporized Alkali atoms (or more generally Alkali-like atoms) therein to an excited state so they precess with the Larmor precession frequency when influenced by magnetic field, a detection assembly typically including a probe light beam directed to pass through the vapor cell, and a detector (such as a photodetector or polarimeter) for detecting the intensity or the polarization of the probe light beam after its passage through the vapor cell. The signals from the detector are processed to detect the scale of the Larmor precession frequency with the ground-state spin polarization of the vaporized Alkali-like atoms, which is indicative of the magnetic field. More specifically, determining the amplitude of the ambient magnetic field $|\mathrm{B}|$ is done by measuring the Larmor precession $\mathrm{w_L}$ frequency of atomic spins of Alkali atoms (according to the relation $|\mathrm{B}| = \frac{\mathrm{w_L}}{\gamma}$ where γ is gyromagnetic ratio).

It should be noted that the phrase *Alkali-like atoms* is used herein to designate any one of the Alkali metal atoms appearing in the first coulomb of the periodic table and/or helium (i.e., the Alkali metals Li, Na, K, Rb, Cs and Fr, as well as He). In other words, the phrase *Alkali-like atoms* is used herein to designate those having a single electron at the outer shell.

An example of an atomic magnetometer is disclosed in IL Patent No. 224958 describing a magnetic field sensing system including at least one magnetic field sensor unit. Each sensor unit includes a sensor cell including an active medium comprising alkali atoms and an optical switch and defining a light propagation channel through the sensor cell. The optical switch is located upstream or downstream of said sensor cell with respect to a direction of light propagation through said light propagation channel, the optical switch being configured and operable to selectively affect light passage through the light propagation channel to thereby selectively activate said sensor cell to provide output light from the sensor unit.

In another example, U.S. Patent No. 10,739,416 discloses a gas cell, a magnetic field measurement device, and a method for producing the gas cell. The gas cell includes a cell main body having a first chamber defined by an inner wall, and a first paraffin film provided on the inner wall, wherein, in the first chamber, a gas which interacts with an electromagnetic wave is stored, the first paraffin film is a pure paraffin film, and a

paraffin constituting the first paraffin film is arranged such that the directions of the molecular axes are aligned.

U.S. Patent No. 7,929,586 discloses an electromagnetic pumped Alkali metal vapor cell system. The system includes a vapor cell and windings. The vapor cell contains Alkali metal and a buffer. The windings are positioned around the vapor cell and are configured to create an electromagnet field in the vapor cell when an AC signal is applied to the windings. The electromagnetic field pumps unexcited Alkali vapor into unionized D1 and D2 states.

PCT Patent Application Publication WO 2012/038948, which is assigned to the assignee of the present application, discloses a large-scale, low cost, array of optical magnetometers in which the basic principle is to use a single light source, which can be more powerful than the individual separate sources, and planar optical elements to direct the light to multiple sites of a sensor array.

U.S. Patent No. 10,725,123, which is assigned to the assignee of the present application, discloses a gradiometer system including one or more magnetic sensor(s). The gradiometer includes an actuation module connectable to the magnetic sensor(s) to vary one or more sensing positions at which a magnetic field is sensed thereby. The one or more sensing positions are varied according to a certain displacement function indicating a predetermined displacement between the sensing positions as a function of time. A controller of the gradiometer system is adapted to determine at least one vector component of a gradient of the magnetic field sensed by the sensor(s) by carrying out the following: (i) obtaining readout data from the sensor(s) indicative of the magnetic field sensed at the varied sensing positions during a certain measurement time duration; (ii) processing the readout data to determine a differential magnetic field time profile indicating a difference between the magnetic fields sensed at least two of the sensing positions during the measurement time duration; and (iii) demodulating the differential magnetic field time profile in accordance with the displacement function to thereby determine a demodulated time profile indicative of the at least one vector component of the gradient of the measured magnetic field.

GENERAL DESCRIPTION

There is a need in the art for a novel and inventive technology for improving the sensitivity, accuracy and robustness of vapor cell-based magnetometers (also known as atomic magnetometers).

In order to provide highly sensitive magnetic field measurements by a magnetometer (e.g., in the scale of pico-tesla), it is preferable to set any electronic component of the magnetometer system, which produces magnetic fields that are not negligible relative to the measurement sensitivity scale, as far as possible from the point of measurement, at which the external/ambient magnetic field is to be measured. In relation to vapor-cell based magnetometers, such an electric component may include for example the light source(s) producing the probe beam, possibly also the pump beam, and possibly also the detector detecting the light beam.

Yet it should be noted that generally obtaining a highly sensitive magnetic field measurement (with improved SNR) requires the probe beam to have a predetermined/steady intensity $\mathbf{I_1}$ and predetermined/steady polarization state P_1 at the input to the vapor cell during the measurement and enable accurate measurement of the magnetic field B. There are various conventional techniques for Larmor Frequency **LF** probing/detection, based on either the intensity $\mathbf{I_2}$ or the polarization state P_2, of the probe light beam at the exit from the vapor cell. These techniques will be readily appreciated by those versed in the art and need not be described here in detail. In order to clarify the need for prior stable setting of both the intensity I_1 and the polarization state P_1 of the probe light beam at its entry to the vapor cell, a non-limiting example of a probing process is hereby discussed. For example, during the probing process, the Alkali-like atoms in the vapor cell are pumped to precess (e.g., via optical and/or electronic/RF pumping). The value the frequency of the precession is the Larmor frequency which corresponds to the magnitude of the magnetic field in the vicinity of the atom. Magnetic resonance transitions can be driven in the atomic ground state by a modulated field at an on-resonance modulation frequency corresponding (synchronized) to the Larmor frequency, and thus, when the optical and/or electronic/RF pumping field are modulated accordingly, the population of the Alkali atoms **AA** are excited to precess coherently. More specifically, when the modulation

frequency corresponds to the Larmor Frequency, a certain ensemble/population of the Alkali-like atoms **AA** are excited to precess. Therefore, typically, in order to measure the magnetic field B, a pumping field is provided (as said above, it may be via optical pumping or electronic/RF pumping), being modulated at a modulation frequency that is swept/varied over a certain modulation frequency range. During this modulation frequency variation (e.g., at various modulation frequencies of the pumping field), the probe light beam **ProbLB** is directed to pass through the vapor cell and is detected/measured after it exists the vapor cell to measure its intensity I_2 or its polarization state P_2.

The probe light beam interacts differently with the Alkali/Alkali-like atoms that do precess at the Larmor Frequency, as compared to Alkali atoms that do not precess. Thus, the population/ensemble of the precessing atoms along the pass of the probe light beam affect its intensity, giving rise to an intensity difference/change $\Delta I = I_1 - I_2$ between the probe light beam's intensity I_1 at the entrance to the vapor cell and its intensity I_2 at the output therefrom. This intensity difference/change **ΔI** is indicative of the population of the precessing Alkali atoms, with which the probe light beam interacts, which is in turn indicative of whether the pumping field is modulated at a frequency corresponding to the Larmor frequency or not.

Moreover, due to the rotational nature of the precession, if the probe light beam includes different circularly-polarized components (e.g. left-circularly-polarized and right-circularly-polarized components), the different circularly-polarized components would interact differently with the precessing atoms, which would result in different relative intensities of the left and right circularly-polarized components of the probe light beam at the exit of the vapor cell, as compared to their relative intensities at the input thereto. Thus, the population of the precessing atoms also affects the polarization state of the probe light beam during its passage through the vapor cell, giving rise to a difference/change $\Delta P = P_1 - P_2$ between the probe light beam's polarization state P_1 at its entrance to the vapor cell and its polarization state P_2 at the output therefrom.

Thus, determining the Larmor Frequency may be achieved by sweeping/varying the modulation frequency of the pumping field (the optical pumping or RF pumping field) across a range (e.g., covering the Larmor frequency), while monitoring the change

in the intensity ΔI or the change in the polarization state ΔP of the probe light beam, as affected by its passage through the vapor cell, during this variation of the modulation frequency (e.g., as a function thereof). At the point (particular-modulation-frequency) along the modulation frequency variation, at which the modulation frequency matches/corresponds to the Larmor frequency, the population of the precessing atoms along the probe beam's path is expected to reach an extremum, and, accordingly, at this point point/particular-modulation-frequency, the change in the intensity ΔI or in the polarization state ΔP of the probe beam is expected to reach an extremum.

Therefore, the Larmor frequency, and hence the measurement the magnetic field B, may be determined by monitoring how the change in at least one of the intensity Δ**I** or the polarization state **ΔP** for the probe light beam as it passes within the vapor cell, is varied as a function of the modulation frequency of the pumping field. The modulation frequency at which this change reaches an extremum is generally indicative of the Larmor frequency, and thus of the magnetic field B which is to be measured (e.g., its magnitude). The accuracy of this measurement is however dependent on having predetermined (i.e., stable) values of both the intensity I_1 and the polarization state P_1 of the probe light beam at the entrance to the vapor cell. This is because the interaction of the probe light beam through its passage in the vapor cell depends on both the intensity I_1 of the probe light beam (which is associated with the number of photons of the beam which are likely to interact with and be absorbed by the population of atoms), as well the polarization state thereof P_1 (since the rate interaction with the precessing atoms depends on the light polarization, and is different between left and right polarizations). Therefore, variations in any one of the intensity I_1 or polarization P_1 of the probe light beam at the entrance to the vapor cell, during the measurement (e.g. during the modulation frequency sweeping/variation) introduces errors/inaccuracies to the magnetic field **B** measurement (since this may affect the location at which the extremum of the change in the intensity Δ**I** or the change in the polarization state **ΔP** appears with respect to the modulation frequency).

Accordingly, in order to obtain an accurate magnetic field measurement, it is desired that both the intensity and the polarization of the probe light beam at the entrance to the vapor cell remain fixed/predetermined and stable. Additionally, as

indicated above, it is desired to place electronic components of the magnetometer system, which produce instrumental magnetic field noises, sufficiently far from the vapor cell, so that their instrumental magnetic field noise at the vapor cell is negligible relative to the measurement sensitivity scale/accuracy. In practice, for example when high measurement accuracy/sensitivity in the order of pico-tesla is sought, this entails placing the light source(s) producing the probe light beam, and possibly the pump light beam (if optical pumping is used), at a distance of a few meters or more (a distance greater than at least one meter) from the point of measurement, the vapor cell.

The conventional techniques are however deficient in fulfilling these two requirements together. Indeed, as will be appreciated by those versed in the art, conveying the light beam(s) from the remote location of the light source(s) to the vapor cell, while maintaining both the intensity and the polarization as stable, may be theoretically possibly (for example utilizing free propagation of the light beam (e.g. laser) from the light source to illuminate the vapor cell), however, in practice, such a setup is not robust, and is prone to failures except if performed in laboratory conditions (e.g. due to various environmental conditions such as temperature-variations, mechanical vibrations of optical elements along the propagation path, and/or contaminants along the path). Likewise, conveying the light beam(s) by utilizing polarization maintaining optical fiber(s) (PMF(s)) extending between the light source(s) and the vapor cell is also not robust, not practical, and prone to failures in non-laboratory conditions. Indeed, although PMF provides good polarization maintenance over short distances (e.g., about less than 1 meter), over larger distances the polarization of a significant part of the light transmitted therethrough is destroyed, thus would hamper the sensitivity of the measurement (this may be caused by various environmental conditions such as mechanical stresses/strains, temperature variations to which the proper functionality of the PMF fiber is susceptible). Indeed, even if one would consider placing a polarizer between the output of a PMF fiber and the vapor cell, to ensure suitable and stable polarization is fed to the vapor cell, in such a setup the partial/non-predetermined and unstable destruction of the polarization of light through the fiber would lead to unstable intensity of light output from the polarizer, and thus in turn also yields reduced sensitivity of the magnetometer. The above affects the

robustness of and/or sensitivity and accuracy of the conventional techniques (e.g., since longer fibers are more susceptible to said environmental conditions, while shorter fibers limit the ability to isolate the measurement point (vapor cell) from other electronic components of the system).

The present invention provides a solution to the above indicated problems in the conventional techniques, and therefore facilitates highly accurate vapor cell based magnetic field measurements to be conducted utilizing a probe light beam (and possibly also a pumping light beam) having a stable (predetermined) intensity and polarization at the entrance to the vapor cell, while placing electronic equipment producing substantial magnetic field noise, such as the light source(s), remote from the location vapor cell, at which the magnetic field is measured.

Thus, according to a broad aspect of the present invention there is provided a magnetometer for measuring a magnetic field B in the vicinity thereof. The magnetometer includes:

- a vapor cell comprising atomic vapor;
- an optical processor for receiving a light beam and directing said light beam, as a probe light beam, to enter the vapor cell with a certain predetermined intensity I_1 and a certain predetermined polarization state P_1 to serve for interacting with at least one type of Alkali-like atoms in the atomic vapor of the vapor cell, for probing a Larmor frequency of precession thereof; and
- a detector for detecting the light beam after interaction with the atomic vapor to generate signals/data indicative of said Larmor frequency.

The optical processor includes an optical depolarizer and a polarizer arranged respectively successively (e.g., not necessarily consecutively) with respect to a propagation direction of said light beam, along a propagation path of the light beam through the optical processor. The optical depolarizer is adapted to depolarize the light beam to yield a depolarized light beam. The polarizer is arranged to polarize the depolarized light beam, to produce said predetermined polarization state P_1 of the light beam, thereby forming said probe light beam with said predetermined intensity I_1 being a predetermined fraction α of an initial intensity I_0 of the light beam and with said predetermined polarization state P_1.

It should be noted that in embodiments of the present invention the *Alkali-like atoms* contained in the vapor cell may include any type of the Alkali metal atoms (e.g. Li, Na, K, Rb, Cs and Fr) and/or helium (He).

In some embodiments of the magnetometer of the present invention, the optical processor is a adapted to output said light beam with said certain predetermined intensity I_1 being the predetermined fraction α of said initial intensity I_0, $I_1 = (\alpha \pm \Delta\alpha) I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of said predetermined intensity I_1 from a nominal value thereof relative to said initial intensity I_0. The optical coupler is configured and operable such that the uncertainty of deviation does not exceed: $\Delta\alpha \leq 10\%$, regardless of an initial polarization state P_0 of said light beam when entering said optical processor **120**, to thereby facilitate accurate determination of the Larmor frequency of precession based on the light captured by said detector.

In some embodiments of the magnetometer of the present invention, the probe light beam is a monochromatic light beam with wavelength λ matching one or more fine-structure absorption lines of the Alkali-like atoms. For example, the one or more fine-structure absorption lines include at least one of a D1 and D2 line of the Alkali-like atoms**.** The monochromatic light beam may, for example, extend over a narrow spectral linewidth $\Delta\nu$ smaller than a shortest separation between two adjacent hyperfine structure transitions of said fine-structure absorption lines of the Alkali-like atoms, to thereby improve a signal to noise ratio (SNR) of light indicative of said Larmor precession captured by said detector.

In some embodiments of the magnetometer of the present invention, the optical processor is adapted to direct said probe light beam to propagate to said vapor cell as a monochromatic polarized light beam having a narrow cross-sectional area, preferably not exceeding $A \leq 80 mm^2$, thereby efficiently producing said probe light beam with a high flux density $F_1 \geq I_1/A \equiv (\alpha \pm \Delta\alpha) I_0/A$. The high flux density F_1 thereby facilitates an efficient interaction of the probe light beam with the Alkali-like atoms, and thereby improves a signal to noise ratio (SNR) of detection of light indicative of said Larmor frequency of precession by said detector.

In some embodiments of the magnetometer of the present invention, the depolarizer includes a pseudo-random, or random, spatial pattern retarder **122.1**

configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area **A** of the light beam. For example, the spatial pattern retarder provides for depolarizing said light beam to a degree of polarization (DoP) equal or lesser than DoP ≤10% when polarizing a narrow monochromatic light beam having wavelength band within the range of $[\lambda \pm \Delta\lambda/2]$ where $\Delta\lambda$ is a full width at half maximum of the wavelength band, does not exceed $\Delta\lambda \leq 1.33$ femto-meter, and at least one of a cross-sectional area A or a diameter D of the beam does not exceed A≤ $19.6mm^2$ or D≤ 5mm respectively. The spatial pattern retarder may, for example, include a layer of liquid crystal polymer (LCP).

It is noted that in some embodiments of the magnetometer of the present invention, the polarizing effect of the polarizer causes attenuation of the light beam passing through the polarizer, by a polarization filtering factor $\alpha_{pol} = 0.5*\pm 0.5*\Delta\alpha_{pol}$ whereby an uncertainty $\Delta\alpha_{pol}$ in the polarization filtering factor $\Delta\alpha_{pol}$ is given by a degree of polarization (DOP) of the light beam output from said depolarizer, $\Delta\alpha_{pol}$ = DoP. Accordingly, the obtained predetermined intensity I_1 of the light beam is a predetermined fraction α of the initial intensity I_0, such that $I_1 = (\alpha \pm \Delta\alpha)I_0 \equiv (\alpha_{a/s} \pm \Delta\alpha_{a/s})(\alpha_{pol} \pm \Delta\alpha_{pol})\ I_0$ (whereby $\alpha_{a/s}$ and $\Delta\alpha_{a/s}$ are respectively an absorption/scattering attenuation factor of the light beam absorption and/or scattering through the optical processor, and $\Delta\alpha_{a/s}$ is a negligible uncertainty in the absorption/scattering attenuation factor $\alpha_{a/s}$, $\Delta\alpha_{a/s}/\alpha_{a/s} \sim 0$). Thus, the maximal deviation $\Delta\alpha$ in the certain predetermined intensity I_1 of the light beam relative to the initial intensity I_0 of the light beam through the optical processor, is given by $I_1/I_{0=}(\alpha \pm \Delta\alpha) \approx \alpha_{a/s}(\alpha_{pol} \pm \Delta\alpha_{pol})$, and the uncertainty in a maximal deviation of the output intensity I_1 relative to the initial intensity I_0 substantially does not exceed the degree of polarization (DOP) of the light beam output from said depolarizer.

In some embodiments of the present invention, the magnetometer is configured for being distanced from a light source (e.g., a laser) producing the light beam by a distance of one or more meters $d \geq 1$m to thereby reduce effects of electromagnetic fields produced by electronics of said light source from affecting measurement of said magnetic field **B** by said magnetometer. For instance, the magnetometer may be associated with an optical fiber extending between said light source and an optical input

of said optical coupler for propagating said light beam to the vapor cell (e.g., to the optical coupler of the magnetometer). Thus, the length of said optical fiber is generally greater than, or equal to the distance of the one or more meters $d \geq 1$m. It is noted that the optical fiber need not maintain polarization of light over this length as the optical coupler obviates a need for the fiber to be configured or function as a polarization maintaining fiber (PMF). In some embodiments of the present invention, optical fiber is a single mode fiber (SMF), thereby providing that said light beam, when exiting said fiber, has a more uniform direction of propagation and/or a more uniform spatial intensity distribution as compared to a multimode fiber of similar length. This thereby improves a signal to noise ratio (SNR) of detection of light indicative of said Larmor frequency of precession by the detector.

It should be noted that the fiber, the light source, or both, may be included as part of the magnetometer. In some implementations the fiber is part of the optical coupler, which couples the light source to the vapor cell.

In some embodiments, the magnetometer of the present invention is configured as an *all-optical* magnetometer. The at least one type of Alkali-like atoms are excited by a pumping light beam, thereby avoiding adverse effects of electromagnetic fields produced by electronic pumping/excitation of the Alkali-like atoms from affecting measurement of said magnetic field by said magnetometer. In such embodiments for example, a single light beam may serve as both the pumping light beam and the probe light beam, and the magnetometer may be, for example, configured with a Bell-Bloom optical setup. Alternatively, all-optical implementations may also be embodied with separate pumping and probe light beams.

In *all-optical* magnetometer embodiments of the present invention, the pumping light beam is preferably circularly polarized in order to improve efficiency of excitation of said Alkali-like atoms thereby. In some embodiments, the pumping light beam is directed to pass through a certain optical processor prior to its entrance to the vapor cell, including an optical depolarizer and a polarizer arranged respectively successively with respect to a propagation direction of the pumping light beam. The certain optical processor may be the optical processor used for the probe beam, or another optical processor.

In some embodiments, the magnetometer of the present invention is configured and operable for probing precession of said Alkali-like atoms utilizing a free induction decay (FID).

In some embodiments of the magnetometer of the present invention, at least one of a frequency, amplitude or polarization of the pumping light beam is modulated at a modulation frequency.

In some embodiments of the magnetometer of the present invention, the detector includes a photodetector capable of detecting a final intensity I_2 of the probe light beam after its passage through the vapor cell. The difference between the predetermined intensity I_1 the probe light beam at the entrance to the vapor cell and the final intensity I_2 is indicative of a Larmor precession frequency of the type of Alkali atoms in the vapor cell.

In various embodiments of the magnetometer of the present invention, the predetermined polarization state P_1 of the probe light beam at the entrance to the vapor cell may be linear polarization, circular polarization, or elliptical polarization. Preferably, in some cases, the predetermined polarization state P_1 of the probe light beam is in circular polarization, in order to improve the rate of interaction of said probe light beam with precessing Alkali atoms.

In some embodiments of the magnetometer of the present invention, the detector comprises a polarimeter capable of detecting data indicative of a change in a state of polarization of probe light beam between its predetermined initial polarization state P_1 and the output/final polarization state P_2 after interaction of the probe light beam with the atomic vapor in said vapor cell. The change of state of polarization of the probe light beam is indicative of a Larmor precession frequency of said type of Alkali-like atoms. For example, the polarizer may be a linear polarizer, to thereby provide that predetermined linear polarization state P_1 at the entrance to the vapor cell including left and right circularly polarized components of the probe light beam. The polarimeter is capable of detecting a difference between the interaction of the left and right circularly polarized components of the probe light beam with the Alkali-like atoms in the vapor cell, whereby said difference is indicative of the Larmor frequency of their precession. The polarimeter may, for example include a differential polarimeter.

In some embodiments of the present invention, the magnetometer is adapted to sweep/vary the frequency of the modulation of the pumping light beam over a range of frequencies, and said detector determines a variation in the difference between said predetermined polarization state P_1 and said output polarization state P_2 or a variation in the difference between said predetermined intensity I_1 and said final intensity I_2, as a function of the frequency of the modulation within the swept varied range of frequencies. The magnetometer then identifies the Larmor frequency, which is indicative of the magnetic field that is to be measured, by identifying an extremum point in said varied difference (between the intensities or between polarization) as a function of the varied modulation frequency.

For instance, in such embodiments the magnetometer may include:

- a modulator capable of modulating said light beam with modulation frequencies within said range, and to output a modulation signal/data indicative of the modulation frequency by which the pumping light beam is modulated;
- a lock-in module adapted to receive the modulation signal/data from the modulator, and connectable to said detector to receive an output detection signal/data thereof; whereby said lock-in module is configured and operable to filter said detection signal/data according to the modulation frequency indicated by said modulation signal/data, and thereby determine at least one of said final intensity I_2 or said output polarization state P_2 of the probe light beam detected by said detector at said modulation frequency; and
- a controller adapted for sweeping/varying the frequency of the modulation over said range of frequencies.

The controller may be adapted to carry out the following at each modulation frequency of one or more modulation frequencies within the range:

- operate said modulator to modulate said pumping light beam with said modulation frequency;
- obtain the final intensity I_2 or said output polarization state P_2 of the probe light beam corresponding to said at least one modulation frequency of the pumping light beam;

- determine a difference between said final intensity I_2 or said output polarization state P_2 and respectively said predetermined intensity I_1 or said predetermined polarization state P_1, of the probe light beam;

The controller may thereby determine the Larmor frequency, based on the difference as determined for the one or more modulation frequencies.

In some embodiments of the magnetometer of the present invention, the detector is associated with an optical collection assembly including one or more optical fibers adapted for receiving the light beam after passage through the vapor cell and coupling said light beam to the detector, whereby the detector is displaced from the vapor cell. For example, the magnetometer may be configured as an *all-optical* magnetometer, and the detector may be displaced from the vapor cell such that instrumental magnetic field noise from the detector, at said vapor cell, is below a designated magnetic field measurement sensitivity to be obtained by the magnetometer system. The detector may be, for example, displaced by a distance of at least 1 meter. To this end, in some embodiments the one or more optical fibers associated with the detector include any one or more of the following fiber types: polarization maintaining fibers, single-mode fibers, or multi-mode fibers.

According to another broad aspect of the present invention there is provided a Bell-Bloom type magnetometer for measuring a magnetic field *B* in the vicinity thereof. The magnetometer includes:

- a vapor cell comprising atomic vapor;
- an optical processor for receiving a light beam and directing said light beam as a monochromatic light beam of wavelength λ matching absorption lines of at least one type of Alkali-like atoms in the atomic vapor, for interacting with said at least one type of Alkali-like atoms , to function as both a pumping light beam and/or a probe light beam;
- A detector for detecting the light beam after interaction with the atomic vapor to generate signals/data indicative of said Larmor frequency; and
- a controller;

In order for the light beam to function as the pumping light beam, the light beam provides a flux *F* of modulated light modulated at a modulation frequency. The

modulation may be a modulation of at least one of a frequency, intensity, or polarization of the pumping light beam, such that when the modulation frequency matches the Larmor frequency, the flux excites magnetic transitions in a population of said atoms along the path of the beam, thereby being at least partially absorbed while causing atom magnetic moments of said population to precess with Larmor frequency $f_L=\gamma B$ according to the magnetic field *B,* which is to be measured. Additionally, in order for the light beam to function as a probe light beam, the light beam is directed with a certain predetermined intensity I_1 and certain predetermined polarization state P_1 to pass through and interact with the population of alkali atoms, and to be detected by the detector, which detects data indicative of at least one of a final intensity I_2 and/or a final polarization state P_2 of the light beam after interaction with the population of atoms.

The controller is adapted for sweeping/varying a frequency of the modulation of the pump light beam over said range of frequencies, and obtain the final intensity I_2 or said final/output polarization state P_2 of the probe light beam detected by said detector at each modulation frequency, to measure, for each modulation frequency, at least one difference of the following:

- an intensity difference $I_2 - I_1$ between the output/final intensity I_2 and said predetermined intensity I_1, whereby said intensity difference is indicative of the absorbance of the light beam by the population of atoms while exciting them to precess;
- a polarization difference $P_2 - P_1$ between said output/final polarization state P_2 and said predetermined polarization state P_1, whereby said polarization difference is indicative of interaction of said light beam with atoms' magnetic moment of said population precessing at the Larmor frequency ,which causes a change in the polarization (spin polarization) state of the atoms (e.g. due to the Faraday Effect);

The controller thereby enables to determine data indicative of said magnetic field B by identifying the Larmor frequency, which is proportionate to the magnetic field B, as the modulation frequency at which said at least one difference is extremal (e.g., maximal).

In some embodiments, the signal to noise ratio in the measurement of said difference is improved by the following configurations:

a. sufficient displacement of an electronic components of a light source producing said light beam from the vapor cell, such that magnetic field noise from said electronic component is reduced in the vicinity of the atoms which are to be excited;

b. sufficient flux of said light beam to improve efficiency of said pumping and increase the population of atoms in which magnetic dipole transitions are excited by the light beam;

c. accurate determination of said certain predetermined intensity I_1 and said certain corresponding predetermined polarization state P_1 to enable determination of said at least one difference with sufficient sensitivity.

The optical processor comprises an optical fiber for connecting the optical processor to the light source, wherein said light source provides a light beam of initial intensity I_0 and is distanced with said sufficient displacement, to thereby reduce said magnetic field noise. Considering that the polarization state of the light beam is prone to deteriorate over a said optical fiber length due to birefringence in fiber (which can be caused by temperature variations or/and mechanical stress and/or manufacturing defects over the fiber), the optical processor also includes an optical assembly for receiving and optically processing the light beam output from the fiber to adjust its certain predetermined intensity I_1 and said certain predetermined polarization state P_1 with accuracy, while maintaining the light beam with a relatively small cross-section A such that the light beam entering the vapor cell has at least said sufficient flux $F_1 = I_1 / A$. The optical assembly includes an optical depolarizer and a polarizer arranged respectively successively with respect to a propagation direction of said light beam along a propagation path thereof through the optical assembly of the optical processor. The optical depolarizer is adapted to scramble (e.g., spatially smear) and depolarize the light beam to yield a depolarized light beam with a reduced degree of polarization DOP and with a predetermined intermediate intensity $I' = (\alpha_{a/s})I_0$ whereby $\alpha_{a/s}$, when passing through at least the optical fiber of said optical processor. The polarizer is arranged to polarize the depolarized light beam, to produce said predetermined polarization state P_1 of the light beam, thereby forming said light beam with said predetermined intensity I_1 being a predetermined fraction $\alpha_{pol} = 0.5*\pm0.5*DOP$ of the intermediate intensity: $I_1 =$

$\alpha_{pol}I' = \alpha_{pol}(\alpha_{a/s})I_0 = (0.5 * \pm 0.5 * DOP)\ (\alpha_{a/s})I_0$ whereby the degree of polarization DOP provided by said depolarizer introduced an uncertainty $\Delta\alpha_{pol}$ to the intensity I_1 of the light beam output from said optical coupler towards said vapor cell. The depolarizer comprises a pseudo-random, or random, spatial pattern retarder, which is configured and operable for spatially randomizing the polarizations of different cross-sectional regions within the small cross-sectional area A of the monochromatic light beam to yield said intermediate light beam with a degree of polarization off less than DoP<10%, thereby improving the accuracy of the predetermined intensity I_1 of the monochromatic light beam with said predetermined polarization state P_1 entering the vapor cell and improving a signal to noise ratio of said measurement.

According to another broad aspect of the present invention there is provided an optical processor configured for receiving a light beam of a certain initial intensity I_0 and undetermined polarization P_0 as an input, and processing said light beam to output said light beam with a certain predetermined intensity I_1 relative to said initial intensity I_0 and certain predetermined polarization state P_1. The optical processor includes an optical depolarizer and a polarizer arranged respectively successively (e.g., not necessarily consecutively) with respect to a propagation direction of said light beam, along a propagation path of the light beam through the optical processor. The optical depolarizer is adapted to depolarize the light beam to yield a depolarized light beam. The polarizer is arranged to polarize the depolarized light beam, to produce said predetermined polarization state P_1 and said certain predetermined relative intensity I_1 of the light beam output of said optical processor.

In some embodiments of the optical processor, the certain predetermined intensity I_1 is a predetermined fraction α of the initial intensity I_0, $I_1 = (\alpha \pm \Delta\alpha)I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of said predetermined intensity I_1 from a nominal value thereof relative to said initial intensity I_0. The optical coupler **120** is configured and operable such that the uncertainty of deviation does not exceed: $\Delta\alpha \leq 10\%$, regardless of an initial polarization state P_0 of said light beam when entering said optical processor.

In some embodiments the light beam processed by the optical processor is a monochromatic light beam. Alternatively, or additionally, in some embodiments the

light beam is designated to pass through a narrow cross-sectional area A≤80mm^2 of the depolarizer.

In some embodiments, the depolarizer includes a pseudo-random, or random, spatial pattern retarder configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area A of the light beam. For example, the pseudo-random, or random, spatial pattern retarder, may include a spatial distribution of at least 40 regions of various retardation properties randomly or pseudo randomly arranged across cross-sectional area of <=1mm^2. For example, the spatial pattern retarder may comprise a layer of liquid crystal polymer (LCP).

The spatial pattern retarder may be adapted to provide for depolarizing the light beam to a degree of polarization (DOP) equal or lesser than DOP ≤10% when depolarizing a narrow monochromatic light beam having wavelength band within the range of [$\lambda \pm \Delta\lambda/2$] where $\Delta\lambda$ being a full width at half maximum of the wavelength band, does not exceed $\Delta\lambda \leq 1.33$ femto-meter (Δf<500MHz), and diameter D of the beam does not exceed D≤10mm.

In some embodiments of the optical processor, a polarizing effect of the polarizer causes attenuation of the light beam passing through the polarizer, by a polarization filtering factor $\alpha_{pol} = 0.5*\pm 0.5*\Delta\alpha_{pol}$ whereby an uncertainty $\Delta\alpha_{pol}$ in the polarization filtering factor $\Delta\alpha_{pol}$ is given by a degree of polarization (DOP) of the light beam output from said depolarizer, $\Delta\alpha_{pol}$ = DoP.

In some embodiments, the optical processor is configured as an all-optical processor, having no electric components. Alternatively, or additionally, the optical processor may include one or more adaptive optical components.

According to yet another broad aspect of the present invention, there is provided a method for optical processing of a light beam to yield the light beam with a certain predetermined intensity I_1 relative to its initial intensity I_0 and with certain predetermined polarization state P_1. The method includes:

- providing a light beam having a certain initial intensity I_0 and undetermined polarization P_0;

- depolarizing said light beam to yield said light beam with a certain intermediate intensity I_{in} relative and substantially un-polarized polarization state;
- subsequent to said depolarizing, polarizing said light beam to yield said predetermined polarization state P_1 and said certain predetermined relative intensity I_1.

The method according to this aspect of the present invention may be configured as an all-optical processing method.

In some embodiments, the predetermined intensity I_1 is a predetermined fraction α of the initial intensity I_0, $I_1 = (\alpha \pm \Delta\alpha) I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of said predetermined intensity I_1 from a nominal value thereof relative to said initial intensity I_0. To this end the method is operable, such that the uncertainty of deviation does not exceed: $\Delta\alpha \leq 10\%$, regardless of an initial polarization state P_0 of the light beam.

In some embodiments of the method, the depolarizing is performed utilizing a pseudo-random, or random, spatial pattern retarder configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area **A** of the light beam.

In some embodiments, the method is adapted to operate with said light beam being a monochromatic light beam. Alternatively, or additionally, the method may be adapted to operate with said light beam having a narrow cross-sectional area $A \leq 80mm^2$. In some embodiments of the method, the depolarizing yields a degree of polarization (DOP) equal or lesser than DOP ≤10% when depolarizing a narrow monochromatic light beam having wavelength band within the range of $[\lambda \pm \Delta\lambda/2]$ where $\Delta\lambda$ being a full width at half maximum of the wavelength band, does not exceed $\Delta\lambda \leq 1.33$ femto-meter, ($\Delta f < 500MHz$), and diameter D of the beam does not exceed $D \leq 10mm$.

In some embodiments of the method, the polarizing affects attenuation of the light beam by a polarization filtering factor $\alpha_{pol} = 0.5 * \pm 0.5 * \Delta\alpha_{pol}$ whereby an uncertainty $\Delta\alpha_{pol}$ in the polarization filtering factor $\Delta\alpha_{pol}$ is given by a degree of polarization (DOP) of the light beam after said depolarizing, $\Delta\alpha_{pol} = DoP$.

According to yet another broad aspect of the present invention there is provided a method for magnetic field measurements. The method includes:

- providing a light beam for probing a vapor cell to determine a Larmor frequency of precession of atomic vapor therein, whereby said light beam is provided from a remote optical source displaced from said vapor cell (e.g., a distance of at least 1 meter), and has a certain predetermined initial intensity I_0 and undetermined initial polarization P_0;
- optically processing said light beam, at a location adjacent to said vapor cell (e.g., located at a distance much smaller than 1 meter from the vapor cell) to yield said light beam with a certain predetermined intensity I_1 relative to said initial intensity I_0 and certain predetermined polarization state P_1, by:
  a. depolarizing said light beam to yield said light beam with a certain intermediate intensity I_{in} and substantially un-polarized polarization state; and
  b. subsequent to said depolarizing, polarizing said light beam to yield said predetermined polarization state P_1 and said certain predetermined relative intensity I_1;
- subsequent to said optical processing, directing said light beam to pass within the vapor cell and interact with the atomic vapor therein for probing a Larmor frequency of precession thereof; and
- detecting at least one of a final polarization state P_2 and a final intensity I_2 of said light beam after interaction with the atomic vapor after and utilizing said at least one of the final polarization state P_2 and the final intensity I_2 to determine the Larmor frequency of precession of the atomic vapor.

In some implementations, the optical processing is carried out according to the optical processing method as described above and in more detail below.

According to further another broad aspect of the present invention there is provided a spatially distributed magnetometer array/network. The network/array includes a plurality of magnetometers for measuring a magnetic field B in respective vicinities thereof. Each magnetometer of one or more magnetometers of the plurality of magnetometers includes:

- a respective vapor cell of the magnetometer, which contains atomic vapor;
- a respective optical coupler for optically coupling between a light source providing a respective light beam for the magnetometer, and the vapor cell of the magnetometer;

The spatially distributed magnetometer network/array includes:

- a reference data provider (e.g., data storage or a network communication module or one or more sensors) capable of providing data indicative of optical attenuation properties of the respective optical couplers of said one or more magnetometers; and
- one or more intensity adjustment modules, associated respectively with said one or more magnetometers, and respectively capable of adjusting the intensities I_1 of the respective light beams of the magnetometers such that at the entrance to the corresponding vapor cells 110 of the magnetometers (e.g. at the outputs from the corresponding optical couplers) the light beams have certain predetermined intensities I_1 ;
- at least one controller connectable to said one or more intensity adjustment modules and configured and operable for operating the one or more intensity adjustment modules according to the optical attenuation properties of the respective optical couplers of the magnetometers associated respectively therewith, to thereby yield said certain predetermined intensities I_1 at the entrance to the vapor cells.

At least one of the light couplers, which is associated with a respective magnetometer of said magnetometers, includes an optical processor configured and operable according to the present invention as described above and, in more detail, below. The optical processor is adapted for receiving the respective light beam of the respective magnetometer, such that it has a certain initial intensity I_0 and undetermined polarization P_0 and processing the light beam to yield/output the light beam with a certain predetermined polarization state P_1 and an intensity I_1 relative to said initial intensity I_0 by an attenuation factor α, $I_1 \approx \alpha I_0$.

In some embodiments, the respective optical attenuation properties of at least some of the light couplers **170** of the spatially distributed magnetometer network/array include compensation for the attenuation factor α of the optical processor.

Alternatively or additionally, in some embodiments where the light couplers **170** include respective optical assemblies (e.g. including one or more optical components along a light propagation path from the light source to the respective vapor cell), the respective optical attenuation properties of the light couplers are associated with the optical attenuation of the optical components of the optical assemblies (e.g. at least for compensation over the attenuation of the optical components which have a relatively substantial attenuation).

For example, in some embodiments, the optical assemblies of one or more of the light couplers **170** include respective optical fibers **140** for propagating respective light beams along at least a part of the light propagation path from the at least one light source to the respective vapor cell. Accordingly, the optical attenuation properties of the at least some of the light couplers **170** may be associated with, or include the attenuation properties of these fibers respectively (e.g. the optical attenuation properties may be indicative of the respective lengths of said fibers).

In some embodiments, the intensity adjustment modules of the spatially distributed magnetometer network/array are each configured and operable for adjusting at least one of the certain initial intensity I_0 and their output intensity I_1 to obtain said certain predetermined intensity I_1 in the respective light beam, at the entrance to their respective vapor cells **110**.

The controller of the spatially distributed magnetometer network/array may be configured and operable for operating the intensity adjustment modules such that the certain predetermined intensities of the light beams are adjusted to a certain similar predetermined intensity I_1 for a plurality of the magnetometers. This thereby provides that accurate comparable values of the magnetic field **B** measurements are obtained by the plurality of magnetometers.

In some implementations, one or more of the magnetometers of the spatially distributed magnetometers network are *All-Optical* magnetometers. For example, one or more of the magnetometers may be configured and operable as Bell-Bloom

magnetometers. Alternatively, or additionally, for example, one or more of the magnetometers may be magnetometers configured and operable according to the present invention as described above and in more detail below.

Specifically, in some embodiments, all the magnetometers of the network may be similar magnetometers configured in at least one of the following configurations:

a. all optical magnetometers;
b. Bell-Bloom magnetometers;
c. magnetometers configured and operable according to the present invention as described above, and in more detail, below.

BRIEF DESCRIPTION OF THE DRAWINGS

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

Fig. 1 is a block diagram schematically illustrating a magnetometer system according to an embodiment of the present invention;

Figs. 2A and 2B are respectively front and perspective views of a random/pseudo-random spatial pattern retarder used as a depolarizer in a magnetometer system according to some embodiments of the present invention;

Fig. 3 is a graphical comparison between the depolarizing properties obtainable with the random/pseudo-random spatial pattern retarder, as compared those obtainable by wedge depolarizer, which make the use of a random/pseudo-random spatial pattern retarder specifically advantageous for incorporation as a depolarizer in the magnetometer system of the present invention;

Fig. 4 is a block diagram schematically illustrating an *All-Optical* magnetometer system configured according to an embodiment of the present invention;

Fig. 5 is a block diagram schematically illustrating an *All-Optical* magnetometer system configured according to an embodiment of the present invention and having a Bell-Bloom configuration;

Fig. 6A is a block diagram schematically illustrating an optical processor according to an embodiment of the present invention;

Fig. 6B is a flow chart of an optical processing method according to an embodiment of the present invention; and

Fig. 7 is a block diagram schematically illustrating a spatially distributed magnetometer array/network according to an embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

Reference is now made to **Fig. 1** schematically illustrating a magnetometer system **100** for measuring an external magnetic field **B** in the vicinity thereof, according to an embodiment of the present invention.

The term external magnetic field **B**, which is also referred to herein interchangeably just as the *magnetic field **B*** is used herein to indicate the magnetic field **B** which is to be measured by the magnetometer system **100**, as opposed to an instrumental magnetic field (being noise), which may be produced by the magnetometer system **100**.

The magnetometer system **100** includes a vapor cell **110** (**VC**) including atomic vapor **AV**, an optical processor **120** located adjacent to the vapor cell **110** (e.g., typically a distance not more than about 20 centimeters) and optically coupled thereto. The optical processor **120** is configured and operable for receiving an incoming light beam **LB(I_0, P=?)** of predetermined/stable intensity I_0 and not necessarily stable/predetermined polarization P, and optically processing the light beam to output a light beam **LB(I_1, P_1)** of stable/predetermined intensity **I_1** and stable/predetermined polarization **P_1**, such that the output light beam **LB(I_1, P_1)** is suitable to function as a probe light beam for probing a vapor cell **110**. The output light beam **LB(I_1, P_1)** is thereafter directed to enter the vapor cell **110**, and the magnetometer system **100** includes a detector **130** for detecting the light beam **LB** after interaction with the atomic vapor **AV** in the vapor cell **110** and, responsive to said detection, generates signals/data indicative of a Larmor frequency **LF** of precession of at least one type of Alkali-like atoms **AA** in the atomic vapor **AV**.

In general, as will be readily appreciated by persons of ordinary skill in the art, any one of various known techniques, such as optical pumping or electronic pumping (e.g., via generation of RF fields in the region of the vapor cell) may be used to pump Alkali-like atoms **AA** to energy levels, at which they precess with the Larmor frequency **LF** corresponding to the magnetic field B which is to be measured in their vicinity.

Probing of the Larmor frequency **LF** of the precessing Alkali-like atoms **AA** is performed optically by utilizing at least a portion, referred to herein as the probe light beam **ProbLB**, of the light beam **LB** that exits the optical processor **120**. In this regard it is noted that, optionally in some embodiments where optical pumping is utilized (see for instance **Fig. 5**), the light beam **LB** processed by the optical processor **120** may include another part/component, being a pumping light beam component, in addition to the component of the light beam **LB** (typically the properties of pumping light beam component are distinct from the probe light beam **ProbLB**, e.g. differently modulated, so that it or its effects can be distinguished from those of the probe light beam **ProbLB** and it does not interfere with the measurement/probing of the Larmor frequency **LF** by the probe beam). In other embodiments where either optical pumping (see for instance **Figs. 4** or **5**) or electromagnetic/RF pumping are used, the light beam **LB** processed by the optical processor **120** may include only the probe light beam **ProbLB** component.

As indicated above, obtaining accurate magnetic field measurement may require that the probe beam (i.e., the light beam **LB** or at least its probe light beam component **ProbLB**) has a predetermined/steady intensity $\mathbf{I_1}$ and predetermined/steady polarization state $\mathbf{P_1}$ at the input to the vapor cell **110** in order to achieve improved SNR and enable accurate measurement of the magnetic field B. This is,, for example because both the intensity $\mathbf{I_1}$ and the polarization state $\mathbf{P_1}$ of the probe light beam **ProbLB** should remain stable/fixed at the entry to the vapor cell **110**, during the modulation frequency sweeping/variation of the pumping field.

As indicated above, the probe light beam **ProbLB** interacts differently with the precessing Alkali-like atoms **AA** as compared to those who do not precess. Accordingly, an intensity difference/change $\Delta\mathbf{I} = \mathbf{I_1} - \mathbf{I_2}$ between the probe light beam's intensity $\mathbf{I_1}$ at the entrance to the vapor cell and its intensity $\mathbf{I_2}$ at the output therefrom, is indicative of the population of the precessing atoms with which the probe light beam **ProbLB**

interacts along its path through the vapor cell. Moreover, due to the rotational nature of the precession, in case the probe light beam **ProbLB** includes different circularly-polarized components (e.g. left-circularly-polarized and right-circularly-polarized components), the different circularly-polarized components thereof would also interact differently with the precessing Alkali-like atoms as compared to their interaction with non-precessing Alkali atoms, and, in this case, a difference/change $\mathbf{\Delta P = P_1 - P_2}$ between the probe light beam's polarization state $\mathbf{P_1}$ at its entrance to the vapor cell and its polarization state $\mathbf{P_2}$ at the output therefrom, would be affected by the population of the precessing atoms with which the probe beam interacts along its path through the vapor cell. Accordingly, a polarization difference/change $\mathbf{\Delta P = P_1 - P_2}$ between the probe light beam's polarization state $\mathbf{P_1}$ at the entrance to the vapor cell and its polarization state $\mathbf{P_2}$ at the output therefrom, may be indicative of the population of the precessing atoms with which the probe light beam **ProbLB** interacts.

Thus, measuring the Larmor frequency **LF** may be achieved by sweeping/varying the modulation frequency of the pumping field (the optical pumping or RF pumping field) across a modulation frequency range, and monitoring the population of the precessing atoms by detecting the change $\Delta\mathbf{I}$ in the intensity or the change $\mathbf{\Delta P}$ in the polarization state of the probe light beam during the modulation frequency sweeping/variation. At the particular-modulation-frequency at which this change in the intensity or polarization state takes place, $\Delta\mathbf{I}$ or $\mathbf{\Delta P}$ is extremal, which is indicative of the Larmor frequency (since, at this modulation frequency, the pumping field is on-resonance with the Larmor frequency, this exciting magnetic resonance transitions the Alkali-like atoms and increases the population of the precessing atoms). Therefore, in order to determine the Larmor frequency and hence measure the magnetic field B, the change in at least one of the intensities $\Delta\mathbf{I}$ or the polarization state $\mathbf{\Delta P}$ for the probe light beam should be measured as a function of the modulation frequency of the pumping field (optical pumping or electronic/RF), and the modulation frequency at which this change reaches extremum is indicative of the Larmor frequency. This is in turn indicative of the magnetic field **B** which is to be measured (e.g., its strength).

Accordingly, as indicated above, the accuracy of the measurement of the magnetic field is dependent on having predetermined (i.e. stable) values of both the

intensity I_1 and the polarization state P_1 of the probe light beam at the entrance to the vapor cell **110** so that the variation in monitored change, in either the intensity or polarization state, **ΔI** or **ΔP**, as a function of the modulation frequency of the pumping, can be attributed to the modulation frequency, and not to some instability in the intensity and/or polarization state of the probe light beam, I_1 and/or P_1, at the entrance to the vapor cell.

Therefore, the optical processor **120** of the magnetometer system **100** of the present invention is adapted to receive at its input optical port **OIn,** a light beam **LB(I_0,P=?)** of stable/predetermined intensity **I_0** (stable/predetermined at least up to a certain accuracy of +-10%) and output from its output optical port **OOut** the light beam **LB(I_1,P_1)** with stable/predetermined intensity **I_1** (predetermined up to about the similar accuracy as the input intensity) and stable/predetermined polarization **P_1**. The optical processor **120** includes an optical depolarizer **122** and a polarizer **126** arranged respectively successively (e.g., not necessarily consecutively) with respect to a propagation direction of the light beam **LB**, along a propagation path **PP** of the light beam through the optical processor **120** (i.e., from its input and output optical ports, **OIn** and **OOut**). The optical depolarizer **122** is adapted to depolarize the light beam to yield a substantially depolarized light beam **LB(I_{im}, P=No)** with certain intermediate intensity (which may be for instance similar to the input intensity **I_0** or attenuated by a certain factor, e.g. due to elements of the optical processor **120**. The polarizer **126** is arranged to polarize the depolarized light beam **LB(I_{im}, P=No)**, to produce the predetermined polarization state **P_1** of the light beam **LB(I_1, P_1)** at the output optical port **OOut**. Thus, the light beam **LB(I_1, P_1)** at the output optical port **OOut** has the predetermined polarization state P_1 as affected by the polarizer **126**, and a predetermined intensity **I_1** being a predetermined fraction α of an initial intensity **I_0** of the light beam **LB(I_0, P_0=?)**. Generally, the predetermined intensity **I_1** of the light beam **LB(I_1, P_1)** at the output is about half of the input intensity due to the polarizer **126** filtering out about half of the unpolarized light **LB(I_{im}, P=No)** (plus some additional typically relatively small attenuation of the light beam which may also take place when the light beam propagates through the optical coupler).

To this end, as indicated above, in order to function as a probe light beam, and enable measurement of the Larmor frequency of precession **LF** and thereby measure the magnetic field **B** with accuracy, the light beam **LB** directed to enter and probe the vapor cell **110** by interacting with the Alkali-like atoms **AA**, should be set to a certain predetermined/stable intensity $\mathbf{I_1}$ and a certain predetermined/stable polarization state $\mathbf{P_1}$ (e.g. stable during the time the modulation frequency of the pumping field is swept/varied and the change in the intensity or polarization of the probe beam is monitored as a function of the modulation frequency).

As indicated above, an additional requirement for obtaining an accurate measurement of the "external" magnetic field **B** (apart from having a stable/predetermined intensity and polarization, $\mathbf{I_1}$ and $\mathbf{P_1}$, of the probe light beam **LB** at the entrance to the vapor cell), is that the instrumental magnetic fields (noise) produced by the magnetometer system **100** itself will vanish in the vicinity of the vapor cell **110**, or be at least negligible with intensity below the required sensitivity δB sought for the magnetic field **B** measurement.

To this end, in some embodiments, the optical processor **120** is configured as an all-optical processor, not including any magnetic field generating electrical components (i.e., not generating instrumental magnetic field noise). In this regard, typically, the optical processor **120** may include only passive optical components (i.e., non- electrically controllable), such as liquid crystal elements, polarizers, phase retarders, lens(es) depolarizers, and spectral filters. However, in some embodiments, the optical processor **120** may also include adaptive optical elements, such as adaptive spectral filters, polarizers or lenses, which may be adaptively adjusted to a desired state of operation, while without inducing instrumental magnetic field noise once they are adjusted to a desired state, or inducing only small instrumental magnetic field much below the tolerated sensitivity δB in the measurement of the external magnetic field **B** (such adaptive optical elements may be, for instance, be set to desired state by application of fixed voltages thereto, with no operational electric current therethrough, so that there is no generation of any instrumental magnetic field noise thereby). It is noted that the term *sensitivity* here designates the noise floor for the measurement (e.g., typically at 1 Hz) or, in other words, the Amplitude magnetic field spectral density at 1Hz.

A source of prominent instrumental magnetic field noise in the magnetometer system **100**, is the light source/pot **150** (e.g., a laser or an output optical port optically coupled thereto) which produces the light beam **LB** and should therefore be optically coupled to the vapor cell **110**.

Therefore, according to some embodiments of the present invention, the light source/port **150** is displaced from the vapor cell **110** by distance **d** such that it affects only negligible instrumental magnetic field noise which is lower than the required measurement sensitivity δB at the vapor cell **110**. In practical implementations of the magnetometer system **100** the displacement distance **d** between the light source/port **150** and the vapor cell **110** is in the order of one or more meters (typically at least a few meters) in order to obtain accurate magnetic field measurements. This is because with typical laser sources suited for producing the light beam **LB**, a displacement of about one or more meters would be required in order to obtain a measurement sensitivity δB not exceeding 5pT/sqrt(Hz) at 1Hz, and a displacement of one or more would be required. For example, with present lasers, in order to obtain a measurement sensitivity δB of 1pT/sqrt(Hz) at 1Hz , an estimated displacement of roughly at least 3 meters is required.

To this end, the optical processor **120** used in the magnetometer system **100** of the present invention facilitates such remote displacement of the light source, while achieving stable/predetermined intensity and polarization, $\mathbf{I_1}$ and $\mathbf{P_1}$, of the probe light beam **LB** at the entrance to the vapor cell. This is despite the fact that obtaining suitable light coupling between the light source/port **150** and the vapor cell **110** over such distances (of one or more meters) while preserving both intensity and polarization of the coupled light, is not practical with conventional light couplers, such as waveguides (single mode or PMFs or other waveguides) or free-propagation based coupling. Indeed, as would generally be appreciated by those versed in the art, in non-laboratory conditions, polarization maintaining waveguides and/or free propagation couplers may preserve polarization and/or intensity only at limited distances, typically of less than several meters, and are susceptible to environmental conditions which, in practice, hamper their proper function to maintain intensity and polarization “(e.g. particularly in

non-laboratory" conditions such as harsh/"field" conditions where typical magnetic surveys take place).

Thus the optical processor **120,** which is used in the magnetometer system **100**, is configured and operable to overcome the above obstacles and couple the light beam **LB** from the light source/port **150** to the vapor-cell **110** over sufficient distance **d** between them (e.g. one or more meters, to reduce/eliminate the effects of the instrumental noise for the light source/port **150** on the magnetic field measurement) while facilitating robust and accurate predetermined intensity and polarization of the light beam **LB** that is coupled to enter the vapor cell **110** so as to enable accurate measurement of the magnetic field **B**.

As shown in **Fig. 1**, the optical processor **120** is generally located in close vicinity to the vapor cell **110** (whose distance is much smaller than the distance **d** between it or the vapor-cell and the light source/port **150**), and may be optically coupled from its output end/port **OOut** to the vapor cell **110** via direct optical coupling (e.g. via physical attachment to an optical window/region at the wall of the vapor cell, or via short free propagation path to such optical window/region), or via a short polarization maintaining waveguide (not specifically shown) which is capable of bridging the short distance between the optical processor **120** and the vapor cell **110** while maintaining both polarization $\mathbf{P_1}$ and intensity I_1 of the light beam **LB(I_1,P_1)** propagating from optical processor **120** to the vapor cell **110** (as said, the distance from the optical processor **120** to the vapor cell **110** is short enough, typically much less than 1 meter, thus enabling preservation of both intensity and polarization via either direct optical coupling of the optical processor **120** to the vapor cell, or by utilizing short polarization maintaining waveguide/fiber). From its input optical port **OIn**, the optical processor **120** is coupled to the light source/port **150**, which is distanced by the distance *d* of one or more meters away, typically by optical fiber/waveguide (e.g., preferably a single mode waveguide, although multimode waveguide may also be used in certain embodiments), or otherwise via free propagation of the light beam **LB** from the light source/port **150** to the optical processor **120**. It should be noted that although (coupling the light beam from the light source/port **150** to the optical processor **120** by free propagation (e.g., through air) is generally possible over limited distances of up to about 3 to 5 meters. As in some

implementations of the system, robust operation is desired with larger distance separating between the light source/port 150 and the optical processor **120**, optical coupling via waveguide, preferably SMF, may preferred in such implementations.

In this regard, it should be noted that optical coupling between the light source/port **150** and the input optical port **OIn** of the optical processor **120** over the distance **d** need not preserve the polarization P of the light beam **LB** provided by the light source **150** or affect it in any predetermined manner but may also totally scramble its polarization without substantially impairing the accuracy of the magnetic field measurement by the magnetometer system **100** of the present invention. On the other hand, the intensity $\mathbf{I_0}$ of the light beam **LB** at the input optical port **OIn** of the optical processor **120** should be predetermined/stable with an accuracy of about +-10%, and thus it may either be measured at the entrance of the optical processor **120**, or otherwise typically the intensity **I** of the light beam **LB** output/produced by the light source/port **150** is known/predetermined (at least to the required 10% accuracy) and also the attenuation of the light during its propagation from the light source/port **150** to the input optical port **OIn** of the optical processor **120** is predetermined/stable (e.g. up to about similar accuracy), so that the intensity $\mathbf{I_0}$ of the light beam **LB** at the input optical port **OIn** is also predetermined/stable.

Thus, according to some embodiments of the present invention, the optical processor **120** is adapted to output the light beam $\mathbf{LB(I_1, P_1)}$ with said certain predetermined/stable intensity $I_1 = (\alpha \pm \Delta\alpha)I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of the predetermined intensity I_1 from its nominal value (relative to the initial intensity I_0). Preferably the optical coupler **120** is configured and operable such that said uncertainty of deviation does not exceed: $\Delta\alpha \leq 10\%$, regardless of the initial polarization state P_0 of the light beam **LB** when entering said optical processor **120** (which is generally unknown). This facilitates accurate determination of said Larmor frequency of precession **LF** based on the light captured by said detector **130**.

Generally, various types of depolarizers may be used as the optical depolarizer **122** of the optical processor **120**. For instance, a wedge type depolarizer may be used.

However, in some embodiments, the light beam **LB** (at least its probe light beam component **ProbLB)** should be preferably monochromatic with a wavelength suitable

for interacting with the precessing Alkali-like atoms **AA** in order to obtain improved SNR and facilitate accurate measurement. More specifically, for example, in order to achieve sufficiently high SNR and accurate magnetic field measurement with measurement sensitivity δB of tens of PicoTesla/sqrt(Hz) at 1Hz or better, the probe light beam **LB(I_1, P_1)**, which is directed to interact with the Alkali atoms **AA** in the vapor cell **110**, should be substantially monochromatic with narrow spectral linewidth Δν substantially smaller than the shortest separation between adjacent hyperfine structure transitions of the fine-structure absorption lines (D1 or D2) of the Alkali atoms **AA** (e.g. absorption lines which are due to spin–orbit interaction in the Alkali atoms **AA**). For example, for Cesium type Alkali atoms the spectral linewidth Δν is less than 1GHz (without any broadening). To this end, in some embodiments, the monochromatic probe light beam **LB** is typically set to extend over only a narrow spectral linewidth Δν that may be for example at least 2-3 times smaller than the shortest separation between two adjacent hyperfine structure transitions of the fine-structure absorption lines (D1 or D2) of the Alkali-like atoms **AA** (such monochromatic light beam covers a range of wavelengths [λ ± Δλ/2] whereby Δν=cΔλ/λ^2 where c is the speed of light.

The optical processor **120** is therefore adapted to direct the probe light beam **LB(I_1, P_1)** to propagate to the vapor cell **110** as a monochromatic and polarized light beam having narrow spectral linewidth Δν as well as predetermined intensity and polarization state, **I_1** and **P_1.**

Moreover, in order to achieve the sufficiently high SNR, the light beam **LB** (at least its probe light beam component **ProbLB)** should preferably also have substantially narrow width/diameter D, with, for example, a mean cross-section width/diameter of about D<10 millimeters. This is in order for the beam's waist to be narrow enough to be distanced from the vapor cell's walls so as to prevent/reduce the probe light beam **ProbLB** interaction with decoherent Alkali-like atoms **AA** near the vapor cell's walls (so that the atomic coherence of the Alkali atoms **AA**, with which the beam interacts, is maintained). In this regard it is noted that the beam typically enters the vapor cell **110** through an optical window of typically small diameter D, e.g. of less than D≤25 mm, so that a small beam width D of about W<10 millimeters is required to displace the beam from the walls at which the atomic coherence of the Alkali atoms is reduced/destroyed

(e.g. due to interactions with vapor cell's walls - which is the reason for confining them by using buffer gas of high enough pressure). Another reason for the use of a probe light beam **LB(I_1, P_1)** having a small width, with the same aim to improve the signal to noise ratio (SNR) of the measurement, is that the probe light beam **LB(I_1, P_1)** should also preferably have sufficiently high flux density *F1* to facilitate an efficient interaction of the probe light beam **LB(I_1, P_1)** with the Alkali-like atoms **AA** in the vapor cell. Therefore, to achieve that, the optical processor **120** may be configured to output the probe light beam **LB(I_1, P_1)** with a relatively narrow cross-sectional area A (for example typically the cross section area A does not exceed $A \leq 80mm^2$, i.e. cross-sectional width of W<9 mm) thereby yielding the probe light beam **LB(I_1, P_1)** with sufficiently high flux density $F1 \geq I_1/A \equiv (\alpha \pm \Delta\alpha)I_0/A$ to enable the efficient interaction thereof with the Alkali atoms **AA** and thereby improve the SNR of the detection.

Thus, for accurate magnetic field measurement, the probe light beam **LB(I_1, P_1)** should be substantially monochromatic (e.g., with spectral line width $\Delta v << 10GHz$) and narrow (e.g. with cross-sectional area $A \leq 80mm^2$ – i.e. beam diameter of about W<9 mm).

To this end, the inventors of the present invention noted that various types or depolarizers may be less suited for use in the optical processor **120** incorporated in the magnetometer system **100**, as they might not provide a sufficiently low degree of polarization when operating on monochromatic and/or on narrow beams. For example, utilizing wedge type depolarizers in the optical processor **120** (such as *a Cornu* depolarizer, quartz-silica or Quartz-quartz wedge depolarizers or any other wedge type depolarizers which are based on the use of wedge/prism of birefringent material) may restrict the accuracy/sensitivity of the measurement of the Larmor precession frequency **LF** by the magnetometer **100**, and thus the accuracy of the measured magnetic field **B**. This is because wedge type depolarizers operate properly for depolarizing light beam to a small degree of polarization, only when the light beam is broadband (e.g., has a broad spectral linewidth Δv in the order of tens of GHz or more), or when the cross-section of the beam spot is significantly wide (e.g., a beam width of at least tens of millimeters). Other types of depolarizers, such as the Cornu depolarizer, are also not suited for depolarizing monochromatic or quasi-monochromatic beams. Time-variable depolarizer

types, such as rotating halfwave plate depolarizers, or adaptive depolarizers, may also not be suited for use in the optical processor **120** as they provide unstable depolarization over time, and their operation may be associated with electronics producing instrumental magnetic field noise in the vicinity of the vapor cell.

Graph **G2** in **Fig. 3** illustrates for example the degree of polarization obtainable by a wedge type depolarizer interacting with such a light beam of monochromatic wavelength λ of about λ = 895nm, as a function of the beam's diameter D. As shown, for any diameter smaller than 10mm, the degree of polarization, DoP, obtained by such a de-polarizer, is relatively high, above 40% percent. This, in turn, means that utilizing such a depolarizer in the optical processor **120** will yield an unstable/un-predictable intensity of the probe light beam at the output of the optical processor **120**. This is because the degree of polarization of the light beam through the polarizer is so high (above 40%), that the intensity filtered by the subsequent polarizer is unknown to about the same factor (40%). Therefore, in this case (where monochromatic and narrow-diameter probe light beam is to be used), utilizing the wedge type depolarizer will not yield an output probe light beam with stable/predetermined intensity I_1.

Therefore, in some embodiments of the present invention, the depolarizer **122** includes, or is a constituted by, a pseudo-random or random spatial pattern retarder **122.1** configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area **A** of the light beam. Accordingly, a beam of light launched into the spatial pattern retarder **122.1** is substantially depolarized, as different cross-sections thereof undergo different polarization variations.

The spatial pattern retarder **122.1** may include, for example, a patterned wave plate, or an arrangement of a plurality of wave plates of various relative retardation phases Γ (e.g., half-wave, quarter-wave, etc.) spatially distributed in a randomized or pseudo-randomized arrangement, such that different cross-sectional regions in the cross-section **A** of the light beam undergo different polarization variations when passing therethrough. The spatial pattern retarder **122.1** may, for example, include a layer of birefringent material, including a plurality of regions having fast and slow axes with several different orientations (e.g., typically at least four), or a spatial arrangement of

birefringent material elements with different orientations of their fast and slow axes. The spatial pattern retarder **122.1** of the optical processor **120** may generally include a passive/static module having a fixed pseudo-random or random spatial pattern of the orientations of its fast and slow axes. Alternatively, or additionally, and although not necessarily needed, the optical processor **120** may optionally also be implemented with an adaptive spatial pattern retarder **122.1** including an arrangement of regions whose retardation relative phases Γ can be adaptively controlled (in this case, care should be taken that, when set, the adaptive setting of the randomized or pseudo-randomized arrangement of different retardation phases will not induce any instrumental magnetic field noise).

To this end, **Figs. 2A and 2B** schematically respectively illustrate, in a self-explanatory manner, the front and perspective views of a random/pseudo-random spatial pattern retarder **122.1** which may be included in, or may constitute, the depolarizer **122** according to some embodiments of the magnetometer system **100** of the present invention. **Fig. 2A** shows the front view of the random/pseudo-random spatial pattern retarder **122.1** where the arrangement of regions of different retardation phases **Γ** at those regions are represented by different grayscale shades (as depicted by the legend on the left of the figure). **Fig. 2A** shows the perspective view of the random/pseudo-random spatial pattern retarder **122.1** where, as shown according to this example, the spatial pattern retarder **122.1** includes a layer of liquid crystal polymer (LCP) with a preset pattern configured to yield the pseudo-random arrangement of regions of the different retardation phases **Γ**.

According to some embodiments of the present invention, the spatial pattern retarder **122.1** is configured such that a beam of light, propagating therethrough, undergoes substantial depolarization, e.g. to a degree of polarization less than $D_OP \leq 10\%$, and even substantially monochromatic components of the light beam, e.g. having spectral linewidth $\Delta\nu$ of a few GHz ($\Delta\nu < 10$ GHz) and in some embodiments having spectral linewidth $\Delta\nu$ in the order of 1GHz or below ($\Delta\nu \leq 1$ GHz), with narrow width $D \leq 10$mm (e.g. cross-section area below $A \leq 80mm^2$) become substantially depolarized to the degree below $D_OP \leq 10\%$.

Graph **G1** in **Fig. 3** illustrates, for example, the degree of polarization obtainable by a spatial pattern retarder **122.1** such as that illustrated in **Fig. 2A**, for a monochromatic light beam as a function of the beam's diameter D. As illustrated for diameter above about 2mm, a high degree of depolarization is obtained (with DoP of about 5% or below). Therefore, as shown, in comparison to the wedge type depolarizers whose depolarization functionality is illustrated in graph **G2**, the random or pseudo-random spatial pattern retarder **122.1** provides an improved degree of polarization for narrow width monochromatic light beams, thus facilitating highly accurate magnetic field measurements when incorporated in the magnetometer system **100** of the present invention.

For example, in some embodiments the spatial pattern retarder **122.1** is configured to provide depolarizing the light beam **LB** (at least its probe beam component **ProbLB**) to a degree of polarization (DOP) equal or less than DOP ≤ 10% where the light beam or its probe beam component is monochromatic with a wavelength band within the range of $[\lambda \pm \Delta\lambda/2]$ where $\Delta\lambda$, which is the full width at half maximum of the wavelength band, does not exceed $\Delta\lambda \leq 1.33$ femto-meter (equivalent to linewidth of about $\Delta v \leq 500$MHz), and its cross-sectional area A or a diameter D of the beam does not exceed A≤ 19.6mm^2 (e.g. its diameter width D does not exceed D≤ 5mm). The wavelength of the light beam **LB** (or at least its probe beam component **ProbLB**) is in this example $\lambda = 895$nm which is suitable for probing the Larmor precession frequency **LF** of the Alkali atoms **AA**.

It should be noted that once the light beam **LB** is depolarized by the depolarizer **122**, the polarizing effect of the polarizer **126** of the optical processor **120** attenuates the light beam **LB** passing through the polarizer, by a polarization filtering factor α_{pol} whereby $\alpha_{pol} = 0.5*\pm0.5*\Delta\alpha_{pol}$ where $\Delta\alpha_{pol}$, being an uncertainty $\Delta\alpha_{pol}$ in the polarization filtering factor, is given by about the degree of polarization in the light beam depolarized by the depolarizer **122:** $\Delta\alpha_{pol}$ = DoP. This is because half of the intensity of the light that is unpolarized by the depolarizer **122** is filtered by the polarizer **126** while the remaining polarized light that is not depolarized by the depolarizer **122** (i.e., the DoP part), depending on its polarization, may or may not be filtered to a certain degree by the polarizer **126**. Thus, the predetermined intensity $\mathbf{I_1}$ of the light beam **LB** output from the

optical processor **120** is a predetermined fraction α of the initial intensity $\mathbf{I_0}$ of the input light beam with uncertainty ±Δα, whereby:

$$I_1 = (\alpha \pm \Delta\alpha) I_0 \equiv (\alpha_{a/s} \pm \Delta\alpha_{a/s})\ (\alpha_{pol} \pm \Delta\alpha_{pol}) I_0$$

where $\alpha_{a/s}$ is a factor representing the attenuation of the light beam through the optical processor **120** due to absorption/scattering which are not due to the polarization manipulation performed by the combination of the depolarizer **122** and the polarizer **126** (e.g. due to absorption by different effects such as spectral filtration, opacity and/or scattering), and $\Delta\alpha_{a/s}$ is an uncertainty in the absorption/scattering attenuation by optical components other than the depolarizer **122** and polarizer **126** of the optical processor **120**. The absorption/scattering attenuation factor by components other than the polarizer $\alpha_{a/s}$ may be a certain predetermined *a priori* known constant characteristic of the considered of the optical processor **120** (which is typically close to unity $\alpha_{a/s \approx 1}$ e.g. unless significantly absorbing optical components such as spectral filters are included in the optical processor **120**. The absorption uncertainty $\Delta\alpha_{a/s}$ is not due to the polarization manipulation performed by the combination of the depolarizer **122** and the polarizer **126** is typically negligible $\Delta\alpha_{a/s}/\alpha_{a/s} \sim 0$, since, in most implementations, the coefficients of optical absorption/scattering by optical components of the optical processor **120** other than the depolarizer **122** and polarizer **126** are generally *a priori* known with accuracy. Accordingly, for simplicity, the maximal deviation Δα in the certain predetermined intensity $\mathbf{I_1}$ of the output light beam **LB** relative to the initial intensity $\mathbf{I_0}$ of the input light beam **LB** is given by:

$$I_1/I_0 = (\alpha \pm \Delta\alpha) \approx \alpha_{a/s}(\alpha_{pol} \pm \Delta\alpha_{pol})$$

where $\alpha_{a/s}$ is typically about 1. Thus, the uncertainty in a maximal deviation of the output intensity I_1 of the light beam **LB** relative to the initial intensity I_0 substantially does not exceed the degree of polarization (DoP) of the light beam output from said depolarizer, since $\Delta\alpha_{pol}$ = DoP. Accordingly, utilizing incorporation of the spatial pattern retarder **122.1** as/in the depolarizer **122** of the optical processor **120** facilitates highly accurate magnetic field measurements, since its output degree of polarization is very low, even for monochromatic narrow beams, and therefore the intensity I_0 of the probe light beam **ProbLB** output from the optical processor **120** (as well as its polarization) can be determined with accuracy, which enables accurate magnetic field measurement.

As indicated above, since the light source/port **150** may be a source of prominent instrumental magnetic field noise, in some embodiments, particularly in cases where high sensitivity of the magnetic field measurements is sought, the magnetometer system **100** is configured such that the light source/port **150** displaces the light source/port **150** from the vapor cell **110** (to which it is optically coupled via the optical processor **120**) by displacement distance **d**, which is selected such that the instrumental magnetic field noise from the light source/port **150** has negligible effect on the SNR/sensitivity δB of the of the magnetic field measurement at the vapor cell **110** (or, in other words, the magnetic field noise ΔB at the vapor cell **110** is lower than the required sensitivity δB of the measurement).

To this end, in some embodiments of the present invention, the magnetometer system **100** is configured such that the light source/port **150** (e.g. the laser producing the light beam **LB** is distanced from the vapor cell **110** by a distance **d** of at least one or more meters $d \geq 1m$ so that its instrumental magnetic field noise does not substantially affect the measurement (i.e. to reduce effects of electromagnetic fields produced by electronics of said light source **150** from affecting measurement of the external magnetic field **B** by magnetometer **100**). Typically, the distance d is greater than one meter, and may be several meters or more. In some embodiments the magnetometer system **100** is associated with, or includes an optical waveguide **140** (e.g., an optical fiber) arranged for propagating the light beam **LB** from the light source/port **150** to the vapor cell **110**. The optical waveguide/fiber **140** may,, for example, extend between the light source/port **150** and the optical processor **120** (e.g. its optical input **OIn**) where the optical output **OOut** of the optical processor **120**, which is adjacent to the vapor cell **110**, may be optically coupled to the vapor-cell **110** for example typically optically coupled directly (or, alternatively, it may possibly be optically coupled by another fiber/waveguide not specifically shown in the figure, being a short polarization maintaining fiber having a length substantially shorter than 1 meter, e.g. not more than a few tens of centimeters, such that the short polarization maintaining fiber does not substantially affect the polarization of the light passing therethrough).

It should be noted that the terms: *optical fiber*, *optical waveguide*, *fiber*, and *waveguide* are used herein interchangeably to designate, in general, any suitable optical

structure (rigid or flexible) capable of guiding optical beams/waves along a certain optical path defined by the waveguide, while restricting transmission of optical energy from outside that optical path.

It should be noted that, typically, polarization maintaining fibers (PMFs) do not operate properly when their length is large (e.g., larger than about one or more meters) and their polarization maintaining property is not adequately maintained with such lengths, as it may be susceptible to mechanical deformations and temperature variations of the fiber along its length. However, the optical processor **120** obviates a need for the optical fiber **140** to be configured or to function as a polarization maintaining fiber over its length d (which is typically greater than one meter, in the order of several meters or longer). This is because, as explained above, given a predetermined initial intensity I_0 and arbitrary polarization of the light beam **LB** which exits the fiber **140** and enters the optical processor **120**, the optical processor **120** is configured to adjust both the polarization and the intensity of the light beam output therefrom to determined values I_1 and P_1. Accordingly, the optical processor **120** obviates a need for utilizing a PMF fiber for guiding the beam from the light source **150** to achieve that goal (and, as said above, practically, conventional PMF fibers are not suited for this purpose over lengths of over 1 meter).

In some embodiments, preferably the optical fiber **140** is configured as a single mode fiber/waveguide (**SMF**). This provides several advantages in the properties of the light beam **LB**, which exits the fiber **140**, and enters the optical processor **120:**

d. With single mode fiber/waveguide (**SMF**) the output light beam **LB** from the fiber **140** has a relatively uniform direction of propagation (e.g., smaller numerical aperture (N/A)) as compared, for example, to multimode fibers/waveguides (MMFs), e.g., since SMF outputs a single ray, as opposed to several rays output by MMF.

e. With single mode fiber/waveguide (**SMF**), the output light beam **LB** from the fiber **140** has typically a Normal (Gaussian) spatial intensity distribution which is more uniform as compared, for example, to multimode fibers/waveguides (MMFs); e.g., since **SMF** outputs a single central

spot/mode, as opposed to several spatially distributed modes/spots output by MMF;

f. With single mode fiber/waveguide (**SMF**) the output light beam **LB** from the fiber **140** maintains a narrower chromatic distribution (e.g., is more monochromatic), as lesser dispersion is affected by SMFs as compared to a comparable MMF of similar length;

At least these advantages make the use of SMF as the fiber **140** preferable in some embodiments of the magnetometer system **100** since it allows the probe light beam **ProbLB** entering the vapor cell to be more monochromatic and have higher flux and more uniform intensity distribution across its cross-section, thereby improving the light-beam's interaction with the Alkali-like atoms **AA**, which are probed along its path and reducing the noise (e.g. due to non-interacting light) sensed by the detector **130**, thus improving a signal to noise ratio(SNR) of detection of light indicative of the Larmor frequency of precession by the detector **130**. Moreover, experiments done by the inventors showed that improved performance of the magnetometer system **100** may be obtained when using an SMF as the input fiber/waveguide **140** to the optical processor **120** (since a lower DoP at the output of the spatial pattern retarder **122.1** of the optical processor **120** may be achieved when SMF is the input fiber **140**, as compared, for example, to the case of using a comparable MMF fiber). As said above, while the optical fiber **140** may, in some embodiments, be configured as an SMF fiber/waveguide, it does not need to be or function as a polarization maintaining fiber (PMF) over its length **d**.

It should be noted that the fiber **140** and/or the light source **150** may be a part of the magnetometer system **100** or may be external modules to which the magnetometer system 100 is adapted to be coupled. In the former case, for example, the fiber **140** may be a part of the optical processor **120** such that it is adapted for optically coupling to a remote light source/port **150** (over a distance of at least **d**) for outputting a light beam, which has both predetermined intensity I_1 and predetermined polarization P_1 (e.g., suitable for probing a vapor cell **110**).

Optionally, in some embodiments, the magnetometer system **100** includes an intensity adjustment module **320** capable of adjusting the intensity I_1 of the light beam **LB** such that at the entrance to the optical processor **120** it has a certain preset initial

intensity I_0 (or otherwise such that at the entrance to the vapor cell **110** it has the certain predetermined intensity I_1). The intensity adjustment module **320** may, for example, include an optical amplifier for adjustably amplifying the intensity of the light beam **LB** to a desired degree and/or an optical attenuator arranged in the propagation path of the light beam **LB** for adjustably attenuating it to a desired degree, and/or it may include a light source controller connectable to light source/port **150** for adjusting its output intensity. As the intensity adjustment module **320** typically includes electronic components, it is typically located remotely from the vapor cell **110** (e.g., near or at the light source port **150** at a distance of about d>1 meter or before the optical fiber **140**) in order to avoid instrumental noise therefrom from having a substantial effect on the measurement. The system **100** may also include a controller **160** connectable to the intensity adjustment module **320** and configured and operable to operate the intensity adjustment module **320** to attenuate or amplify the light beam **LB** to a controllable degree to yield certain predetermined intensities I_1 of the light beam **LB** at the entrance to the vapor cells **110**. To this end, the controller **160** may, for example, utilize data/signals indicative of the optical attenuation properties of the respective optical processor **120** and or the fiber **140** and/or of any other optical component along the beam's path from the light source/port **150** (as well as possibly data/signals indicative of the intensity output from the light source/port **150**) and operate the intensity adjustment module **320** according to these optical attenuation properties to attenuate or amplify the light beams to a designated intensity I_1 at the entrance to the respective vapor cell **110**.

As indicated above and would be readily appreciated by those versed in the art, in the example of **Fig. 1**, the Alkali-like atoms **AA** may be pumped to energy levels, at which they precess with the Larmor frequency **LF**, by any one of various known in the art techniques, such as by optical pumping or by electronic (e.g., RF) pumping. However, in some embodiments of the present invention, in which particularly sensitive magnetic field measurements are sought, use of optical pumping is preferable over electronic/RF pumping. This is because instrumental magnetic field noise sourced by electronic/RF pumping may deteriorate the allowable measurement sensitivity. Indeed, also with optical pumping, the laser optical-source/port used to source the pumping field may

also introduce instrumental magnetic field noise interfering with the measurement sensitivity. To resolve that, and to facilitate high sensitivity magnetic field measurement, the present invention provides a technique for placement of the optical light source/port **150** remote from the vapor cell **110**, so as to avoid/reduce its instrumental magnetic field noise from interfering with the measurement, while still enabling determination of the properties (intensity and polarization) of the probe's light **ProbLB** entering the cell **110** cell to allow the measurement.

Figs. 4 and 5 exemplify two embodiments of the magnetometer system **100** of present invention configured with an *All-Optical* setup, in which both the pumping of the Alkali-like atoms **AA**, as well as the probing of their Larmor frequency of precession **LF**, are performed optically. This provides for further diminishing of the magnetic field noise in the vicinity of the vapor cell **110**, since the Alkali atoms **AA** are excited/pumped by the pumping light beam **PumpLB** thereby avoiding adverse effects of electromagnetic fields produced by electronic pumping/excitation of the Alkali atoms (e.g. due to electromagnetic source in the vicinity of the atomic vapor, or any electric wires/coils, laser drivers, photodiodes power supplies, etc.) from affecting measurement of said magnetic field by said magnetometer.

It should be understood that the magnetometer systems **100** in the embodiments of **Figs. 4 and 5** may include/incorporate any, or all, of the essential features, components and functions which are described above in relation to the magnetometer system **100** of **Fig. 1**, as well as the optional features, components and/or functions described in relation to the magnetometer system of **Fig. 1**. Accordingly, for clarity, similar/like reference numerals, as in **Fig. 1**, are maintained also in **Figs. 4 and 5,** and are used to designate similar components, features and/or functions. It should be understood that the above descriptions of these components, features and/or functions, as presented in relation to the magnetometer system of **Fig. 1**, also apply to the embodiments of **Figs. 4 and 5** (possibly with proper adaptations to the embodiments in those figures, as would readily be appreciated by those versed in the art) and, for clarity and conciseness, and are not repeated in relation to **Figs. 4 and 5.**

Fig. 4 is a block diagram illustrating the magnetometer system **100** of the present invention according to an *All-Optical* embodiment thereof, in which the pumping light

beam **PumpLB** and the probe light beam **ProbLB**, are configured as separate light beams (e.g., propagating to the vapor cell along to distinct optical paths). As shown, since the polarization and intensity of the pumping light beam **PumpLB** need not be specifically known/maintained for carrying out the measurement, it does not need to necessarily pass-though, or be processed-by, an optical processor, such as the optical processor **120** by which the probe light beam **ProbLB** is processed before entering the vapor cell **110** (accordingly, a relatively more energy efficient optical pumping is achieved, as compared to the embodiment of **Fig. 5**, since, as said above, the processor **120** attenuates to about half the intensity of light beam processed thereby).

Fig. 5 is a block diagram illustrating the magnetometer system **100** of the present invention according to an *All-Optical* embodiment thereof configured and a so-called *Bell-Bloom* optical setup, in which a single light beam **LB** is configured for, and functions, for both the pumping/excitation of the Alkali-like atoms **AA** as well as for the probing/detection of their Larmor frequency. Thus, the probe and the pump light beam components **ProbLB + PumpLB** of the single light beam **LB**, are processed together by the optical processor **120**, as shown in the figure.

Referring together to the embodiments shown in both **Figs. 4 and 5**, it should be noted that the source/port **154** of the pumping light beam **PumpLB** is preferably separated from the vapor cell **110** by a distance d of one or more meters, to prevent/reduce instrumental magnetic field noise from interfering with the measurement of the external magnetic field B at the vapor cell **110**. Similarly, as described above with respect to the probe light beam **ProbLB**, the pumping light beam may generally be arranged to propagate from its source/port **154** towards the location of the vapor cell along a free propagation path. However, in some embodiments, in which a more robust setup is required, the magnetometer system may include a waveguide/fiber **144** for guiding the pumping light beam **PumpLB** towards the region of the vapor cell **110** (in the Bell-Blum configuration of **Fig 5**, the source/port **154** of the pumping light beam **PumpLB** may be the same as the source/port **150** of the probe light beam **ProbLB**, and both the pumping light beam **PumpLB** and the probe light beam **ProbLB** may typically be directed to propagate via the same waveguide **140** towards the optical processor **120**).

It should be noted that in some implementations the magnetometer system may be configured and operable for probing precession of said Alkali-like atoms utilizing a free induction decay (FID). In such embodiments the pumping light beam **PumpLB** need not be necessarily modulated.

In some embodiments, at least one of a frequency, amplitude, or polarization of said pumping light beam **PumpLB** is modulated at a modulation frequency.

In some implementations, the properties of pumping light beam **PumpLB** are somewhat different from those of probe light beam **ProbLB**. Alternatively, in some implementations pumping light beam component **PumpLB** and the probe light beam component **ProbLB** are actually implemented by a single laser source and implemented by a single beam, thereby having similar properties.

To this end, in some embodiments of the magnetometer system **100**, the pumping light beam **PumpLB** is modulated. The modulation may, for example, be a frequency modulation (FM) and/or an amplitude modulation (AM) and/or polarization/helicity modulation (PM) and/or any other suitable modulation which a person of ordinary skill in the art would consider suitable. It is understood that in embodiments, e.g., in a *Bell-Bloom* setup where the pump beam functional component and the probe functional component are implemented via a single light beam, both components are similarly modulated. The magnetometer system **100** may, for example, include a modulator **154.M** configured for applying the modulation to the pumping light beam **PumpLB** (and possibly also the probe light beam/component **ProbeLB**).

To this end, in some implementations the magnetometer **100** may be adapted to measure the magnetic field **B** by carrying out the following:

(i) Applying a modulation to the pumping light beam **PumpLB** (e.g., by utilizing the modulator **154.M**). The pump beam may be, for example, modulated in amplitude (AM), frequency (FM) and/or polarization (PM) at a certain modulation frequency, which, when it becomes similar to the Larmor frequency, excites the states of the Alkali atoms;

(ii) Sweeping/Varying the frequency of the modulation through a plurality of modulation frequencies over a range of frequencies (e.g., by controlling/adjusting the modulator's **154.M** operation);

(iii) Measuring the final intensities I_2 and/or the final polarization states P_2 of the probe light beam **ProbLB**, as obtained when the pumping light beam **PumpLB** is modulated by different modulation frequencies of the plurality of modulation frequencies, across which the modulation is swept/verified. The final intensities I_2 and/or the final polarization states P_2 are measured on the probe light beam **ProbLB** after it had interacted with the Alkali atoms **AA**, e.g., after it had excited the vapor cell **110**. The measurement may be carried out by utilizing the detector **130**, for example by a photodetector **132** capable of measuring light intensity or by a polarimeter capable of measuring polarization state;

(iv) Determining the difference ΔI between the predetermined intensity I_1 and the final intensity I_2 or determining the difference ΔP between predetermined polarization state P1 and the output polarization state P_2 as a function of the plurality of modulation frequencies, across which the modulation is swept/verified. For example, per each modulation frequency of said plurality of modulation frequencies, a controller/computer **160** determines/computes the change ΔI or ΔP;

(v) Then, identifying the Larmor frequency LF, which is indicative of the measured magnetic field **B** according to the modulation frequency, bringing the difference ΔI or ΔP to an extremum point. For example, according to the modulation frequency in which the difference/change in the intensity ΔI or polarization ΔP of the probe beam **ProbLB** is maximal or minimal (e.g., depending on the configuration of the magnetometer system **100**).

Thus, according to some embodiments of the present invention, the magnetometer system **100** may include a controller **160** that is configured and operable for operating the system **100** to carry out the above operations (i) to (v) for measuring the magnetic field **B**.

It should be understood that the terms *controller* or *control system*, as used herein interchangeably, may refer to an analog and/or digital circuit, and/or to a computer exactable code implementable on a digital processor, or a combination

thereof, which is configured and operable for carrying out the controlling functions for which it is designed. The controller may include or be associated with an input for receiving input data/signals pertaining to its operation, and a driver or an output for outputting data or signals, which result from the controller's operation, and are provided to the system/module controlled by the controller for controlling their operation accordingly. A person of ordinary skill in the art will readily appreciate how to implement the controllers with the configuration described in the present application using any one of various known technologies.

The magnetometer system **100** may optionally include a modulator **154.M** capable of modulating the pumping light beam **PumpLB** with modulation frequencies within a certain modulation frequency range appropriate for determining the Larmor frequency LF. The suitable modulation frequency range for detecting magnetic fields of certain magnitudes, will be generally known to those versed in the art. For example: for measurement of magnetic fields B of magnitudes in the order of 15µT-100µT and the modulation frequency range may be 52.5kHz-350kHz when using for Cesium atoms, or, in another example, when using Rubidium, it may be in the range of 105kHz-700kHz. For example, the controller **160** may provide the modulator **154.M** with signal/data **ModSig** indicative of the modulation frequency by which it is to modulate the beam at each time. In this example, the magnetometer system **100** may also include a lock-in module **130.M** adapted connectable to receive the detection signal/data **DetSig** from the detector **130** and configured and operable to filter the detection signal/data **DetSig** according to the modulation frequency indicated by the modulation signal/data **ModSig**, and thereby determine obtain filtered signal/data **FltSig** indicative of at least one of the final intensity I_2 or the output polarization state P_2 of the probe light beam **ProbLB** detected by the detector **130** at the respective modulation frequency.

As indicated above, in some embodiments the controller **160** is adapted for sweeping/varying the frequency of the modulation over the range of frequencies and carrying out the following at each modulation frequency of one or more modulation frequencies within said range:

a. operate the modulator **154.M** to modulate the pumping light beam **PumpLB** with the modulation frequency;

b. obtain the final intensity I_2 or the output polarization state P_2 of the probe light beam **ProbLB** as obtained corresponding to the respective modulation frequency of the pumping light beam **PumpLB**;

c. determine a difference ΔI or ΔP, between the final intensity I_2 predetermined initial intensity I_1 or between the final polarization state P_2 and the predetermined initial polarization state P_1, of the probe light beam **ProbLB** per each of the plurality of modulation frequencies;

d. determine/compute the Larmor frequency LF based on this difference, ΔI or ΔP, as determined for said one or more modulation frequencies.

It should be noted that, typically, in implementations such as illustrated in **Fig. 5**, where a single beam **LB** is used for both the pump-beam **PumpLB** and the probe-beam **ProbLB**, typically both the pump-beam **PumpLB** and the probe-beam **ProbLB** components of the single beam **LB** (e.g., from a single source) are modulated. Then, at the detection path, the modulation of the probe beam components is filtered for example by a locking amplifier, in order to obtain a detection signal indicative of the measured Larmor frequency.

In implementations such as illustrated in **Fig. 4** where there are separate beams, pump-beam **ProbLB** and the probe-beam **ProbLB**, the pump beam **PumpLB** is typically modulated (its amplitude, frequency and/or polarization), while the probe beam **ProbLB** need not necessarily be modulated.

It some embodiments where such configuration is possible, the pumping light beam **PumpLB** is preferably circularly polarized to improve the efficiency of excitation of the Alkali atoms by the pumping light beam **PumpLB**.

Optionally, in some embodiments, before entering the vapor cell **110**, the pumping light beam **PumpLB** is directed to pass through a certain optical processor **120'** configured and operable for outputting the pumping light beam **PumpLB** with or determined/stable intensity and polarization towards the vapor cell **100**. The configuration of the certain optical processor **120'** may be similar to that of the optical processor **120** and it may include an optical depolarizer and a polarizer (not specifically shown in the figure) arranged respectively successively with respect to a propagation direction of said pumping light beam **PumpLB** (it is noted that the types of the

depolarizer and the polarizer of the optical processor **120'** may optionally be different than those of the optical processor **120**. The certain optical processor **120'** which may be used pumping light beam **PumpLB** may be the same as the optical processor **120** used for the probe light beam **ProbLB,** as shown in **Fig. 5** in which the pumping light beam **PumpLB** and the probe light beam **ProbLB** are directed along a common optical path and may be considered components of the same beam. Alternatively, the certain optical processor **120'** operating on the pumping light beam **PumpLB** may be separate/different to as the optical processor **120** operating on the probe light beam **ProbLB**, as optionally shown in **Fig. 4**.

The above method for measurement of the magnetic field B is exemplified with reference to the *All-Optical* embodiments of the magnetometer system **100** of the present invention in which optical pumping is used, as illustrated in **Figs. 4 and 5**. In this regard it should be understood that the present invention is not limited by this specific measurement method, and a person of ordinary skill in the art will readily appreciate other measurement methods which can be implemented to measure magnetic fields utilizing various embodiments, *All-Optical* or electronically/RF-pumped, of the magnetometer **100** of the present invention.

Referring now together to **Figs 1, 4 and 5**, as indicated above, the measurement of the magnetic field may be based on measurement of either the final intensity I_2 or final polarization state P2 of the probe light beam after its interaction with the Alkali-like atoms **AA** in the vapor cell **110**.

In embodiments where intensity measurement is used, the detector **130** typically includes a photodetector **132** capable of detecting a final intensity I2 of the probe light beam **ProbLB** after passage through the vapor cell **110**. The Larmor precession frequency **LF** of the Alkali atoms **AA**, and thus the magnetic field B, is thereby determined based on the measured difference between the predetermined intensity I1 and the final intensity I2 of the probe light beam **ProbLB**. It should be noted that in such embodiments, where intensity-based measurement is used, the polarization state P_1 of the probe beam **ProbLB** may be linear, circular, or elliptical. Preferably the polarization state P_1 of the probe beam **ProbLB** is circular polarization to thereby improve the rate of interaction of said probe light beam **ProbLB** with precessing Alkali atoms.

In embodiments where polarization measurement is used, the detector **130** typically includes a polarimeter **134** capable detecting/obtaining data/signals indicative of the final state of polarization P2 of the probe light beam **ProbLB** after its interaction with the Alkali atoms **AA** in the vapor cell **110** (or the difference ΔP between the final and initial polarization states, P2 and P1). It is noted that the term *polarimeter* is used herein to designate generally any suitable type of polarization detector, for example a regular-polarimeter, or a differential-polarimeter.

To this end, in some embodiments the polarizer **126** of the optical processor **120** is a linear polarizer, providing that the predetermined polarization state P_1 is linear and includes both left and right circularly polarized beam components of the probe light beam **ProbLB**. Accordingly, the polarimeter **134** is capable of detecting a difference between the interaction of the left and right circularly polarized beam components of the probe light beam with the Alkali atoms **AA** in the vapor cell **110**, and said difference is indicative of the population of Alkali atoms **AA** precessing with the Larmor frequency.

As indicated above, the detector **130**, which should also be optically coupled to the vapor cell **110**, may present another source of instrumental magnetic field noise (which may be of lesser magnitude than the noise produced by the light source/port(s) e.g. **150, 154**). However, introducing a displacement between the detector **130** and the vapor cell **110** that is sufficient to yield its instrumental magnetic field noise of the detector **130** negligible at the vapor cell **110**, is less problematic (as compared to displacement of the light source **150**) because various measurement schemes may require only the information of one of the intensity I_2 and polarization P_2 of the light beam after its propagation through the vapor cell **110** to be preserved and detected by the detector **130**. This facilitates optical coupling between the vapor cell **110** and the detector **130** from a distance.

Indeed, in some embodiments where the detector **130** includes a photodetector **132** and the magnetic field is measured by measuring the intensity I_2 of the probe light beam **ProbLB** after its passage through the vapor cell **110**, one or more optical fibers (e.g. a single fiber) may be used for coupling the vapor cell **110** to the photodetector **132** over a distance of 1 meter or more, or even a few meters or more, while robustly

preserving the information of the intensity I_2 of the probe light beam **ProbLB** after its output from the vapor cell **110**.

Alternatively or additionally, in embodiments where the detector **130** includes a polarimeter **134** and the magnetic field is measured by measuring the polarization state P_2 of the probe light beam **ProbLB** after its passage through the vapor cell **110**, at least one polarization maintaining fiber may be used for coupling the vapor cell **110** to the photodetector **132** over distance in the order of 1 meter (while independently carrying at least two polarization components of the light beam), or at least two optical fibers, which need not be necessarily PMFs, and may be arranged for separately carrying the two polarization components of the probe light beam **ProbLB** to the polarimeter **134** over even larger distances than one meter. In the latter case for example, a polarization beam splitter (e.g., a Wollaston prism) may be arranged between the vapor cell and two optical fibers for splitting the two polarization components of the probe light beam **ProbLB** to propagate separately through the two fibers to the detector or different balanced photodetectors **130**. Accordingly, utilizing one of the above configurations, probe light beam **ProbLB** may be coupled to the detector **130** over a distance of one meter or more, while robustly preserving the information of the polarization P_2 of the probe light beam **ProbLB** after its output from the vapor cell **110**.

Thus, according to some embodiments of the present invention the magnetometer is configured as an all-optic magnetometer, and the detector is displaced from the vapor cell with a distance configured such that, at said vapor cell, the instrumental magnetic field noise from the detector **130** is below a designated magnetic field measurement accuracy/sensitivity to be obtained by the magnetometer system **100**. For example, the detector **130** may be displaced from the vapor cell **110** by a displacement distance (not specifically shown in the figures) of at least one or more decimeters or even higher, i.e., at a distance of one or more meters.

The magnetometer system **100** may include an optical collection assembly **142**, including for example one or more optical fibers/guides that are adapted for receiving the light beam **LB** after its passage through the vapor cell **110** and optically coupling it with the detector **130**. The optical collection assembly **142** includes, for example, one or

more optical fibers/guides. The optical collection assembly **142** may include for example:

a. one (or more) optical fibers (not necessarily PMFs) when intensity measurement is used;

b. one (or more) PMF optical fibers or two or more not necessarily PMFs fibers, when polarization measurement is used.

This facilitates the magnetometer's configuration as a fully all-optic magnetometer with no electrical component in the vicinity of the vapor cell **110** (at least none which generate an instrumental magnetic field noise).

This may be particularly practical in embodiments where the magnetic field **B** is measured based on the intensity I_2 of the light beam **LB** (i.e., the detector **130** is a photodetector) and there may be no need to preserve the final polarization P_2 of the probe beam **LB** after its interaction with the vapor cell **110**. In this respect, the intensity-based measurements (i.e., the detector **130** is a photodetector **132**) may be advantageous over polarization based measurements in terms of their ability to measure small magnetic fields B, since it allows the detector to be distanced to relatively large distances from the vapor cell, thus practically avoiding instrumental magnetic field noise from the detector **132**.

Reference is now made to **Figs. 6A and 6B** schematically illustrating, in a block diagram and a flow chart respectively, an optical processor **120** and a method **200** for optical processing of a light beam **LB** according to an embodiment of the present invention.

The optical processor **120** is configured for receiving a light beam **LB** of a certain initial intensity I_0 and undetermined polarization P_0 as an input, and processing said light beam **LB** to output the light beam **LB** with a certain output intensity I_1 relative to said initial intensity I_0 and certain predetermined polarization state P_1. The optical processor **120** includes an optical depolarizer **122** and a polarizer **126** arranged respectively successively (e.g., not necessarily consecutively) with respect to a propagation direction of the light beam **LB**, along a propagation path **PP** thereof through the optical processor **120**. The depolarizer **122** is adapted to depolarize the light beam **LB** to yield a depolarized light beam. The polarizer **126** is arranged to subsequently polarize the

depolarized light beam, to produce the predetermined polarization state P_1 and the relative intensity I_1 of the light beam **LB** output from the optical processor **120**.

Typically, the certain relative output intensity I_1 is a predetermined fraction α of the initial intensity I_0, $I_1 = (\alpha \pm \Delta\alpha) I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of the output intensity I_1 from a nominal value thereof relative to the initial intensity I_0. In some implementations the optical processor **120** is configured and operable such that the uncertainty of deviation does not exceed $\Delta\alpha \leq 10\%$, regardless of the initial polarization state P_0 of the light beam **LB** when entering the optical processor **120**.

In some embodiments the depolarizer **122** includes a pseudo-random, or random, spatial pattern retarder **122.1** that is configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area **A** of the light beam. This for example facilitates that the processed light beam **LB** be a substantially monochromatic light beam, for instance the light beam may have a wavelength band $\Delta\lambda$ with full width at half maximum in the order of several hundreds of femto-meters or even less i.e., and in some cases wavelength band $\Delta\lambda$ not exceeding a few Femto-meters (e.g. $\Delta\lambda \leq 1.33$ Femto-meter).

The pseudo-random, or random, spatial pattern retarder **122.1** may include a spatial distribution of tens or more regions of various retardation properties (preferably hundreds or thousands of regions), randomly or pseudo randomly arranged across the cross-sectional area of the depolarizer **122**, through which the light beam **LB** is designated to pass. In some embodiments the light beam **LB** is designated to pass through a narrow cross-sectional area $A \leq 80mm^2$ of the depolarizer **122** or smaller, for example in the order of several mm^2 or even less than 1 mm^2 (e.g. use of a light beam **LB** of narrow cross-sectional area A of $3mm^2$ was experimented successfully by the inventors, and the result of said experiment provided indication that the technique of the present invention may be operated with beams of even narrower cross-sectional area A for example of $0.3mm^2$).

To this end, in some embodiments, the spatial pattern retarder **122.1** provides for depolarizing of the light beam to a degree of polarization (DoP) equal or lesser than DoP ≤10% when depolarizing a narrow monochromatic light beam having wavelength band within the range of $[\lambda \pm \Delta\lambda/2]$ where $\Delta\lambda$ is a full width at half maximum of the

wavelength band, in the order of one or more Femto-meters, and diameter D of the beam in the order of a few millimeters.

The spatial pattern retarder **122.1** may for instance include a layer of liquid crystal polymer (LCP) with a spatial distribution of tens or more regions of various retardation properties (preferably hundreds or thousands of regions), randomly or pseudo randomly arranged across the cross-sectional area of the depolarizer **122**.

As indicated above in the discussion with reference to **Fig. 1**, the polarizing effect of said polarizer causes attenuation of the light beam passing through the polarizer, by a polarization filtering factor $\alpha_{pol} = 0.5*\pm 0.5*\Delta\alpha_{pol}$ whereby the uncertainty $\Delta\alpha_{pol}$ in the polarization filtering factor $\Delta\alpha_{pol}$ is given by a degree of polarization (DOP) of the light beam output from said depolarizer. The output intensity I_1 is therefore a predetermined fraction α of the initial intensity I_0, such that $I_1 = (\alpha\pm\Delta\alpha)I_0 \equiv (\alpha_{a/s}\pm\Delta\alpha_{a/s})\ (\alpha_{pol}\pm\Delta\alpha_{pol})\ I_0$ whereby $\alpha_{a/s}$ and $\Delta\alpha_{a/s}$ are respectively an absorption/scattering attenuation factor of the light beam absorption and/or scattering through the optical processor **120** ($\Delta\alpha_{a/s}$ is typically negligible, so the maximal deviation $\Delta\alpha$ in the output intensity I_1 of the light beam relative to the initial intensity I_0 of the light beam through the optical processor, is given by $I_1/I_0=\alpha_{a/s}(\alpha_{pol}\pm\Delta\alpha_{pol})$.

Optionally, in some embodiments the optical processor **120** includes an intensity adjustment module **320** capable of adjusting the intensity of the light beam **LB** such that the output intensity I_1 is set to a designated value. The intensity adjustment module **320** may, for example, include an optical amplifier for adjustably amplifying the intensity of the light beam **LB** to a desired degree, and/or an optical attenuator arranged in the propagation path of the light beam **LB** for adjustably attenuating it to a desired degree, and/or it may include a light source controller adapted to adjust the intensity of the source. To this end, the optical processor **120** may include a controller (not specifically shown in the figure) that is configured and operable to operate the intensity adjustment module **320** to attenuate or amplify the light beam **LB** by a controllable degree to yield the designated output intensity I_1 thereof.

Optionally the optical processor **120** may include additional optical components along the optical path of the beam **LB**, such as lenses, filters diffractive elements, or other optical components as may be required for the optical processing purpose for

which the optical processor **120** may be used. In some implementations one or more of such additional optical components may also be adapted optical components, whose optical effect on the beam is controllable/adjustable. For example, one such adaptive optical component may be the optional intensity adjustment module/utility **320** described above.

In some embodiments the optical processor **120** may be configured as an *All-Optical* processor having no electric components. Alternatively, or additionally, in some embodiments the optical processor **120** may be configured as a pseudo-*All-Optical* processor in the sense that it does not include electrically controlled components near the output port **OOut** at which the beam exits the optical processor **120**. In the latter case, electronically controlled adaptive optical components (such as the optional intensity adjustment module **320**), if such, are included in the optical processor **120**, and are preferably located remotely from the output port **OOut**, e.g., by a distance of one or more meters.

Referring to **Fig. 6B** a method **200** for optical processing of the light beam **LB** which may be implemented by the optical processor **120** is diagrammatically illustrated in a self-explanatory manner. The method includes the following operations:

210: providing a light beam **LB** having a certain initial intensity I_0 and undetermined polarization P_0. Optionally, **212**– the light beam **LB** may be substantially monochromatic as indicated above. Optionally, as also indicated above, **214** – the light beam **LB** may have a narrow characteristic cross-sectional area A (narrow diameter characteristic diameter D).

230: depolarizing the light beam **LB** to yield the light beam **LB** with certain intermediate intensity I_{in} relative to the initial intensity I_0 and un-polarized polarization state. Optionally, as indicated above, **232 –** the depolarizing may be carried out by utilizing a random spatial pattern retarder **122.1** for spatially randomizing the polarizations of a plurality of different cross-sectional regions within a cross-sectional area **A** of the light beam. This facilitates the depolarization of a light beam which is either monochromatic, has narrow width, or both, to a high degree of depolarization (e.g., DOP below 10% or even below 5%).

250: subsequent to the depolarizing **230**, polarizing the light beam **LB** to the designated predetermined polarization state P_1 as required at the output. Accordingly, in **270**: yielding the light beam **LB** with a certain predetermined intensity I_1 relative to said initial intensity I_0 and the required predetermined polarization state P_1.

290 (optional): The method may optionally include adjustment to the initial intensity I_0 of the light beam **LB** in accordance with a designated intensity I_1 required at the output and in accordance with the intensity attenuation, which is affected on the light beam **LB** during the processing (for example by operations **230** and **250**). This will yield the light beam **LB** at the output having a designated intensity I_1 and the designated predetermined polarization state P_1.

Other variations of the method **200**, or additional optional operations which may be incorporated in the method **200**, will be readily appreciated by those versed in the art, and/or may be readily understood in light of the detailed description above regarding the optical processor **120**.

In some cases, particularly in cases where there is a need to spatially map a magnetic field **B** over a certain region/axis x, B(x), or to determine the gradient $\partial_x\mathbf{B}$ or gradient mapping $\partial_x\mathbf{B(x)}$ of the magnetic field B, a plurality of magnetic field measurements of the field B are needed at a number of points/locations at that region/axis x. Particularly in cases where the spatial map of the magnetic field B is required with high accuracy/sensitivity (e.g., sensitivity δB in the order of several Pico-Tesla at 1Hz or better), vapor cell based magnetometers, such as those discussed above with reference to **Figs 1, 4 and 5**, may be used at the different locations in the region x. The plurality of measurements at the different locations are required to be relatively accurate and sensitive (i.e., accurate relative to one another) to provide such mapping accurately. In some embodiments this may be achieved by utilizing sensitive vapor cell magnetometers configured according to the present invention, as illustrated for instance in **Fig. 1**, and preferably by utilizing *All-Optical* magnetometers, such as those shown in **Fig. 4 and 5**, as they provide higher signal to noise ratio (SNR). Indeed, slight variations in the intensity I_1 of the probe light beam **ProbLB** at the input into the vapor cell **110** has no significant effect on the accuracy/sensitivity of the measurement when a single measurement (e.g., at a single location) is concerned. However, when

considering a plurality of measurements over the region x for mapping the magnetic field **B** in that region x, carried out by a plurality of the magnetometers **100**, slight variations in the intensities I_1 of the probe light beams **ProbLB** input into the vapor cells **110** and the magnetometers **100** at the different locations may result in poor relative accuracies of the measurements by the different magnetometers **100** thus impairing the collective sensitivity of the mapping the magnetic field **B** in that region x.

To this end, reference is now made to **Fig. 7** in which a spatially distributed magnetometer array/network **300**, according to an embodiment of the present invention, is schematically illustrated. The spatially distributed magnetometer array/network **300** includes a plurality of magnetometers **{100.i}** for measuring a magnetic field *B* in a region x (in respective vicinities of the magnetometers). In this non-limiting example, three magnetometers **{100.1, 100.2 and 100.i}** are illustrated as an example. However, it should be clear that any number of magnetometers may be included in the network/array **300**. The region x over which said mapping is to be performed may be one, two, or three dimensional, and the magnetometers **{100.i}** of the network may be arranged accordingly.

As shown, each magnetometer **100.i** of the one or more magnetometers **{100.i}** of said plurality includes at least the following components:

a. a respective vapor cell **110** of the magnetometer **100.i** which contains atomic vapor **AV**;

b. a respective optical coupler **170** of the magnetometer **100.i** for optically coupling between a light source **150** providing a respective light beam **LB.i** (e.g., a probe-beam or probe+pump beam) for the magnetometer **100.i**, and the vapor cell **110** of said magnetometer **100.i**;

The spatially distributed network/array **300** includes:

c. a reference data provider **310** (e.g., data storage or a network communication module or one or more sensors) which are capable of providing data indicative of the optical attenuation properties of the respective optical couplers **170** of the one or more magnetometers **{100.i}**. For instance, predetermined data indicative of the respective optical coupler's **170** attenuation properties may be stored and a data storage

(remote or local), or any suitable sensors/or sensory channels, may be used to determine said attenuation properties.

d. one or more intensity adjustment modules **{320.i}** capable of adjusting the intensities I_1 of the respective light beams **LB.i** of the magnetometers **{100.i}** such that at the entrance to the corresponding vapor cells **110** of the magnetometers (e.g., at the outputs from the corresponding optical couplers **170**) the light beams **LB.i** have certain predetermined intensities I_1. For instance, the intensity adjustment modules {**320.i}** may include optical amplifier(s) and/or optical attenuator(s) arranged in the propagation paths of the respective light beam {**LB.i}** of the different magnetometers which are capable of amplifying or attenuating the intensity of the light beam by an adjustable degree of amplification/attenuation **LB**. Alternatively or additionally, the intensity adjustment modules {**320.i}** may include light source controller(s) connectable to light source(s)/port(s), e.g. **150.1** to **150.i** of the light source module/system **150** and adapted for adjusting the output intensity of the respective light sources/ports; and

e. at least one controller **360** connectable to the one or more intensity adjustment modules **{320.i}** and to the reference data provider **310** and configured and operable to carry out the following:

    (i) obtain the optical attenuation properties of the respective optical couplers **170** from the reference data provider **310**;

    (ii) operate the one or more intensity adjustment modules **{320.i}** according to the optical attenuation properties of the respective optical couplers **170** of the magnetometers **{100.i}** to attenuate or amplify the respective light beams **{LB.i}** by controllable degrees to yield certain predetermined intensities I_1 of the light beams **{LB.i}** at the entrance to respective the vapor cells **110** of their associated magnetometers, and thereby facilitate an accurate and sensitive magnetic field mapping at the region **x**. It is noted that the controllable degrees of attenuation/amplification may be determined by the controller

based on the optical attenuation properties of the respective optical couplers **170** and based on data indicative of the intensities of the light beams **{LB.i}** at the output from the light source system/module **150** – where the latter may be predetermined and/or may be measured/calculated (for example using the power consumption of the light sources {**150.i**}) and/or it may be indicated by data (e.g. which may be provided or stored by reference data provider **310**).

It should be clarified that in various implementations the light source system/module **150**, may or may not be a part of the spatially distributed magnetometer network/array **300** of the present invention, or may be external thereto. The light source system/module **150** may include one light source/port (e.g., **150.1**; e.g., a laser) or several light sources/ports (e.g., **150.1, 150.2, 150.i**; e.g., several lasers) and may be a single or distributed system. In embodiments where a common light source/laser **150.1** is used for several magnetometers, a beam splitter module **152** may be included to split the beam from the light source to the several magnetometers.

It should be noted that in some embodiments, high relative accuracy between the magnetic field **B** measurements by the different magnetometers **{100.i}** is obtained when their respective light beams **LB.i** have similar predetermined intensities at the entrance to their respective vapor cells. Accordingly, in such embodiments, the controller **360** may be configured and/or operable for operating the intensity adjustment modules **{320.i}** such that the certain predetermined intensities I_1 of the light beams **LB.i** are adjusted to such certain similar predetermined intensity I_1 for a plurality of said magnetometers **{100.i}**, to thereby obtain accurate and comparable values of the magnetic field **B** measurements by the plurality of magnetometers **{100.i}**.

It is noted that the light couplers **170** typically include respective optical assemblies, each including one or more optical components along the respective light propagation path of its respective light beam from the light source module **150** to its respective vapor cell **110**. Accordingly, the respective optical attenuation properties of the light couplers **170** are associated with (i.e., are a function of) the optical attenuation

of their respective optical components, particularly of those having a relatively substantial attenuation e.g., in the order of one or more percent, or even less.

To this end, as illustrated in **Fig. 7**, the optical assemblies of one or more of the light couplers **170** may include respective optical fibers **140** for propagating the respective light beam along at least a part of the light propagation path from the light source module/system **150** to the respective vapor cell **110**. As the optical fibers **140** may be relatively long in order to displace the electronics from the vapor cell (e.g., to avoid instrumental noise, as discussed above), the respective optical attenuation properties of the light couplers **170** may be primarily determined/representative of the attenuation properties of their respective fibers respectively (unless additional components of relatively high attenuation are included in the optical assemblies, in which case the attenuation of such components may also need to be taken into account in the respective optical attenuation properties of the light couplers). Thus, in some embodiments, the optical attenuation properties of the light couplers **170** as provided/stored by the data provider **310** may be indicative of, or represented by, the lengths of the optical fibers **140** of the respective optical couplers **170** (e.g., the respective optical attenuation properties of at least some of the light couplers **170** may be indicative of respective lengths of their fibers **140**). It should be noted that in some embodiments the light couplers **170** of all of the magnetometers **{100.i}** of the network/array **300** may include respective optical fibers **140**.

It should be noted that in some implementations the optical assemblies of one or more of the light couplers **170** may include adaptive optical components, whose light attenuation factors/properties may vary depending on their adaptive state. In such cases the data provider **310** may be configured and operable to provide data indicative of the attenuation factors/properties of the optical couplers corresponding to the adaptive state(s) of such components.

As indicated above, in some implementations accurate/sensitive magnetic field measurement by a magnetometer **100.i** is obtained when both the polarization state P_1 and the intensity I_1 of the respective light beam **LB.i** of the magnetometer **100.i** are known at the entrance to its vapor cell **110**. For the reasons explained in detail above, particularly due to the need to displace the vapor cell **110** from the light source system

150 by a significant distance **d** and the lack of polarization maintaining fibers over such distance, the light beam **LB.i** may arrive at the vicinity of the vapor cell with undefined polarization. Accordingly, in some embodiments of the invention, the light couplers **170** of one or more of the magnetometers {**100.i}** (particularly those whose vapor cells are displaced in relatively large distance from the light source system/module **150**, and who are equipped with fiber to carry the light beam from the light source module **150** to the vapor cell **110**; typically all) include respective optical processor **120** located adjacent to the vapor cell (e.g. by a small distance, preferably not exceeding a few tens of centimeters, or more preferably not exceeding 10 centimeters). The optical processor **120** is configured and operable for receiving the respective light beam **LB.i** of the respective magnetometer **100.i**, whereby the light beam has a certain initial intensity I_0 and undetermined polarization P_0 and processes the light beam **LB.i** to yield the light beam **LB.i** with a certain predetermined polarization state P_1 and a certain intensity I_1 at the entrance to the vapor cell **110**.

The optical processor **120** may generally be configured and operable according to an embodiment of the optical processor **120** and the optical processing method **200** as described in detail in the present application, for example with reference to **Figs. 1 to 6B** above.

As indicated above, the light attenuation properties of such an optical processor **120** may be significant (e.g., tens of percent). Accordingly, the respective optical attenuation properties of the light couplers **170**, as provided by the data provider **320** may be representative/inclusive of the attenuation properties of their respective optical processor **120** part of the optical couplers **170** (as well as possibly other components of the optical couplers, such as the fibers **140**). In other words, the respective optical attenuation properties of the at least some of the light couplers **170** include compensation for the attenuation factor α of their respective optical processor **120**.

As exemplified in the non-limiting example of **Fig. 7**, the intensity adjustment modules **{320.i}** may be configured and operable for adjusting the initial intensity I_0 of the light beam at the entrance to the optical processor **120,** at the entrance to the vapor cell **120** (or at the output of the optical processor **120)** or the intensity of the light output from the light source system **150**, or during its propagation from the light source to the

optical coupler **170** or optical processor **120** (see for example the different locations of the adjustment modules **{320.i}** in the figure.

It should be noted that the spatially distributed magnetometer network/array **300** of the present invention may be configured with one or more of said magnetometers **{100.i}** as *All-Optical* magnetometers. Specifically, the *All-Optical* magnetometers **{100.i}** may be configured with Bell-Bloom configuration. In some embodiments, the spatially distributed magnetometer network/array **300** of the present invention may be configured and operable as an accurate and sensitive *All-Optical* magnetometer network/array in which all the magnetometers **{100.i}** are at least one of:

a. all optical magnetometers.
b. Bell-Bloom magnetometers.
c. magnetometers configured and operable according to any one of the embodiments of **Figs. 4 and 5** above, or according to any other suitable *All-Optical*, vapor cell based, magnetometer system, as known or will be known in the art.

CLAIMS

[Claim 1]

A magnetometer for measuring a magnetic field *B* in the vicinity thereof, the magnetometer comprising:

a vapor cell comprising atomic vapor;

a optical processor for receiving a light beam and directing said light beam, as a probe light beam, to enter the vapor cell with a certain predetermined intensity I_1 and certain predetermined polarization state P_1 to serve for interacting with at least one type of Alkali-like atom in the atomic vapor of the vapor cell, for probing a Larmor frequency of precession thereof; and

a detector for detecting the light beam after interaction with the atomic vapor to generate signals/data indicative of said Larmor frequency;

wherein the optical processor comprises an optical depolarizer and a polarizer arranged respectively successively (e.g. not necessarily consecutively) with respect to a propagation direction of said light beam, along a propagation path of the light beam through the optical processor; wherein the optical depolarizer is adapted to depolarize the light beam to yield a depolarized light beam LB(I_{im}, P=No); and the polarizer is arranged to polarize the depolarized light beam, to produce said predetermined polarization state P_1 of the light beam, thereby forming said probe light beam LB(I_1, P_1) with said predetermined intensity I_1 being a predetermined fraction α of an initial intensity I_0 of the light beam LB(I_0, P_0=?) and with said predetermined polarization state P_1.

[Claim 2]

The magnetometer of claim 1 wherein said optical processor is a adapted to output said light beam LB(I_1, P_1) with said certain predetermined intensity I_1 being the predetermined fraction α of said initial intensity I_0, $I_1 = (\alpha \pm \Delta\alpha) I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of said predetermined intensity I_1 from a nominal value thereof relative to said initial intensity I_0, and wherein said optical coupler is configured and operable such that said uncertainty of deviation does not exceed $\Delta\alpha \leq 10\%$, regardless of an initial polarization state P_0 of said light beam when entering said optical

processor, to thereby facilitate accurate determination of said Larmor frequency of precession based on the light captured by said detector.

[Claim 3]

The magnetometer of claim 1 or 2 wherein said probe light beam is a monochromatic light beam with wavelength λ matching one or more fine-structure absorption lines of the Alkali-like atoms.

[Claim 4]

The magnetometer of claim 3 wherein the monochromatic light beam extends over a narrow spectral linewidth $\Delta\nu$ smaller than a shortest separation between two adjacent hyperfine structure transitions of said fine-structure absorption lines of the Alkali-like atoms, to thereby improve a signal to noise ratio (SNR) of light indicative of said Larmor precession captured by said detector.

[Claim 5]

The magnetometer of any one of claims 1 to 4 wherein said optical processor is adapted to direct said probe light beam LB(I_1, P_1) to propagate to said vapor cell as a monochromatic polarized light beam having a narrow cross-sectional area preferably not exceeding A≤80mm^2, thereby efficiently producing said probe light beam with a high flux density $F_1 \geq I_1/A \equiv (\alpha \pm \Delta\alpha) I_0/A$; said high flux density F_1 thereby facilitates an efficient interaction of the probe light beam LB(I_1, P_1) with the Alkali-like atoms and thereby improves a signal to noise ratio (SNR) of detection of light indicative of said Larmor frequency of precession by said detector.

[Claim 6]

The magnetometer of any one of claims 1 to 5 wherein said depolarizer comprises a pseudo-random, or random, spatial pattern retarder configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area A of the light beam.

[Claim 7]

The magnetometer of claim 6 wherein said spatial pattern retarder provides for depolarizing said light beam to a degree of polarization (DoP) equal or lesser than DoP ≤10% when polarizing a narrow monochromatic light beam having wavelength band within the range of [λ ± Δλ/2] where Δλ being a full width at half maximum of the wavelength band , does not exceed Δλ ≤ 1.33 femto-meter, and at least one of a cross-sectional area A or a diameter D of the beam does not exceed A≤ $19.6mm^2$ or D≤ 5mm respectively.

[Claim 8]

The magnetometer of claim 6 or 7 wherein said spatial pattern retarder comprises a layer of liquid crystal polymer (LCP).

[Claim 9]

The magnetometer of any one of claims 1 to 8 wherein a polarizing effect of said polarizer causes attenuation of the light beam passing through the polarizer, by a polarization filtering factor α_{pol} = 0.5*±0.5*$\Delta\alpha_{pol}$ whereby an uncertainty $\Delta\alpha_{pol}$ in the polarization filtering factor $\Delta\alpha_{pol}$ is given by a degree of polarization (DOP) of the light beam output from said depolarizer, $\Delta\alpha_{pol}$ = DoP.

[Claim 10]

The magnetometer of claim 9 wherein the predetermined intensity I_1 is a predetermined fraction α of the initial intensity I_0, such that $I_1 = (\alpha \pm \Delta\alpha)I_0 \equiv (\alpha_{a/s} \pm \Delta\alpha_{a/s})(\alpha_{pol} \pm \Delta\alpha_{pol})\ I_0$ whereby $\alpha_{a/s}$ and $\Delta\alpha_{a/s}$ are respectively an absorption/scattering attenuation factor of the light beam absorption and/or scattering through the optical processor, and $\Delta\alpha_{a/s}$ is a negligible uncertainty in said absorption/scattering attenuation factor $\alpha_{a/s}$, $\Delta\alpha_{a/s}/\alpha_{a/s} \sim 0$, so that a maximal deviation $\Delta\alpha$ in the certain predetermined intensity I_1 of the light beam relative to the initial intensity I_0 of the light beam through the optical processor, is given by $I_1/I_{0=}(\alpha \pm \Delta\alpha) \approx \alpha_{a/s}(\alpha_{pol} \pm \Delta\alpha_{pol})$ whereby an uncertainty in a maximal deviation of the output intensity I_1 relative to the initial intensity I_0

substantially does not exceed the degree of polarization (DOP) of the light beam output from said depolarizer.

[Claim 11]

The magnetometer of any one of claims 1 to 10 configured for being distanced from a light source (e.g., a laser) producing said light beam by a distance *d* of one or more meters $d \geq 1$m to thereby reduce effects of electromagnetic fields produced by electronics of said light source from affecting measurement of said magnetic field B by said magnetometer.

[Claim 12]

The magnetometer of claim 11 being associated with an optical fiber of length greater than, or equal to, said distance *d* of the one or more meters, extending for propagating said light beam between said light source and an optical input of said optical processor; and wherein said optical processor obviates a need for said fiber to be configured and function as a polarization maintaining fiber (PMF) over said length.

[Claim 13]

The magnetometer of claim 12 wherein said optical fiber is a single mode fiber (SMF) thereby providing that said light beam, when exiting said fiber, has a more uniform direction of propagation and/or a more uniform spatial intensity distribution as compared to a multimode fiber of similar length, thereby improving a signal to noise ratio (SNR) of detection of light indicative of said Larmor frequency of precession by said detector.

[Claim 14]

The magnetometer of any one of claims 1 to 13 configured as an *all-optical* magnetometer, whereby said at least one type of Alkali-like atoms are excited by a pumping light beam, thereby avoiding adverse effects of electromagnetic fields produced by electronic pumping/excitation of the Alkali-like atoms from affecting measurement of said magnetic field by said magnetometer.

[Claim 15]

The magnetometer of claim 14 configured with a Bell-Bloom optical setup wherein said light beam serves as both said pumping light beam and said probe light beam.

[Claim 16]

The magnetometer of claim 14 wherein said pumping and said probe light beams are separate light beams.

[Claim 17]

The magnetometer of any one of claims 14 to 16 wherein said pumping light beam is preferably circularly polarized to improve efficiency of excitation of said Alkali-like atoms by the pumping light beam.

[Claim 18]

The magnetometer of any one of claims 14 to 17 wherein said pumping light beam is directed to pass through a certain optical processor prior to its entrance to the vapor cell and wherein said certain optical processor is said optical processor or another optical processor, and comprises an optical depolarizer and a polarizer arranged respectively successively with respect to a propagation direction of said pumping light beam.

[Claim 19]

The magnetometer of any one of claims 14 to 18 configured and operable for probing precession of said Alkali-like atoms utilizing a free induction decay (FID).

[Claim 20]

The magnetometer of any one of claims 14 to 19 wherein at least one of a frequency, amplitude or polarization of said pumping light beam is modulated at a modulation frequency.

[Claim 21]

The magnetometer of any one of claims 1 to 20 wherein said detector comprises a photodetector capable of detecting a final intensity I_2 of said probe light beam after passage through the vapor cell; said predetermined polarization state P_1 of the probe light beam is any one of a linear polarization, a circular polarization, or an elliptical polarization; and wherein a difference between said predetermined intensity I_1 and said final intensity I_2 is indicative of a Larmor precession frequency of said type of Alkali atoms.

[Claim 22]

The magnetometer of claim 21 wherein said predetermined polarization state P_1 of the probe light beam is preferably circularly polarization to improve the rate of interaction of said probe light beam with precessing Alkali atoms.

[Claim 23]

The magnetometer of any one of claims 1 to 22 wherein said detector comprises a polarimeter capable of detecting data indicative of a change in a state of polarization of probe light beam between its predetermined initial polarization state P_1 and the output/final polarization state P_2 after interaction of the probe light beam with the atomic vapor in said vapor cell; whereby said change of state of polarization of probe light beam is indicative of a Larmor precession frequency of said type of Alkali-like atoms.

[Claim 24]

The magnetometer of claim 23 wherein said polarizer is a linear polarizer, thereby providing that said predetermined polarization state P_1 is a linear polarization comprising left and right circularly polarized beam components of the probe light beam.

[Claim 25]

The magnetometer of claim 24 wherein said polarimeter is capable of detecting a difference between the interaction of the left and right circularly polarized beam components of said probe light beam with the Alkali-like atoms in the vapor cell.

[Claim 26]

The magnetometer of any one of the claims 20 to 25 adapted to sweep/vary a frequency of the modulation over a range of frequencies, and utilizing said detector to determine a variation in the difference between said predetermined polarization state P_1 and said output polarization state P_2 or a difference between said predetermined intensity I_1 and said final intensity I_2, as a function of the frequency of the modulation within said range of frequencies, and identifying said Larmor frequency, which is indicative of said magnetic field that is to be measured, by identifying an extremum point of said difference as a function of the modulation frequency.

[Claim 27]

The magnetometer of any one of the preceding claims, wherein the detector is associated with an optical collection assembly including one or more optical fibers adapted for receiving the light beam after passage through the vapor cell and coupling said light beam to the detector, whereby the detector is displaced from the vapor cell.

[Claim 28]

The magnetometer of claim 27 wherein said magnetometer is an all-optic magnetometer and the detector is displaced from the vapor cell such that instrumental magnetic field noise from said detector at said vapor cell is below a designated magnetic field measurement sensitivity to be obtained by said magnetometer system.

[Claim 29]

An optical processor configured for receiving a light beam of a certain initial intensity I_0 and undetermined polarization P_0 as an input and processing said light beam

to output said light beam with a certain predetermined intensity I_1 relative to said initial intensity I_0 and certain predetermined polarization state P_1

wherein the optical processor comprises an optical depolarizer and a polarizer arranged respectively successively (e.g. not necessarily consecutively) with respect to a propagation direction of said light beam, along a propagation path of the light beam through the optical processor; wherein the optical depolarizer is adapted to depolarize the light beam to yield a depolarized light beam; and the polarizer is arranged to polarize the depolarized light beam, to produce said predetermined polarization state P_1 and said certain predetermined relative intensity I_1 of the light beam LB output of said optical processor.

[Claim 30]

The optical processor of claim 29 wherein said certain predetermined intensity I_1 is a predetermined fraction α of the initial intensity I_0, $I_1 = (\alpha \pm \Delta\alpha) I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of said predetermined intensity I_1 from a nominal value thereof relative to said initial intensity I_0, and wherein said optical coupler is configured and operable such that said uncertainty of deviation does not exceed $\Delta\alpha \leq 10\%$, regardless of an initial polarization state P_0 of said light beam when entering said optical processor.

[Claim 31]

The optical processor of claim 29 or 30 wherein said depolarizer comprises a pseudo-random, or random, spatial pattern retarder configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area A of the light beam.

[Claim 32]

The optical processor of any one of claims 29 to 31, configured for operating with said light beam having at least one of the following configurations, or both:

- said light beam is a monochromatic light beam; and

- said light beam is designated to path through a narrow cross-sectional area A≤80mm^2 of said depolarizer;

wherein preferably said spatial pattern retarder provides for depolarizing said light beam to a degree of polarization (DOP) equal or lesser than DOP ≤10% when depolarizing a narrow monochromatic light beam having wavelength band within the range of [λ ± Δλ/2] where Δλ is a full width at half maximum of the wavelength band, does not exceed Δλ ≤ 1.33 femto-meter (Δf<500MHz), and diameter D of the beam does not exceed D≤10mm.

[Claim 33]

The optical processor of any one of claims 29 to 32 configured as an all-optical processor.

[Claim 34]

A method for optical processing of a light beam comprising:

providing a light beam having a certain initial intensity I_0 and undetermined polarization P_0 to yield said light beam with a certain predetermined intensity I_1 relative to said initial intensity I_0 and certain predetermined polarization state P_1 ;

depolarizing said light beam to yield said light beam with a certain intermediate intensity I_{in} relative and substantially un-polarized polarization state; and

subsequent to said depolarizing, polarizing said light beam to yield said predetermined polarization state P_1 and said certain predetermined relative intensity I_1.

[Claim 35]

The method of claim 34 wherein at least one of the following:

- said predetermined intensity I_1 is a predetermined fraction α of the initial intensity I_0, $I_1 = (\alpha \pm \Delta\alpha) I_0$, whereby $\Delta\alpha$ designates an uncertainty of deviation of said predetermined intensity I_1 from a nominal value thereof relative to said initial intensity I_0, and wherein the method is operable such that said uncertainty of deviation does not exceed Δα ≤10%, regardless of an initial polarization state P_0 of said light beam;

- said depolarizing is performed utilizing a pseudo-random, or random, spatial pattern retarder configured and operable for spatially randomizing the polarizations of different cross-sectional regions within a cross-sectional area **A** of the light beam.

[Claim 36]

The method of any one of claims 34 to 35 adapted to operate with said light beam configured in at least one of the following, or both:

- said light beam being a monochromatic light beam;
- said light beam having a narrow cross-sectional area $A \leq 80mm^2$.

[Claim 37]

The method of any one of claims 34 to 36 wherein said depolarizing yields a degree of polarization (DOP) equal or lesser than DOP ≤10% when depolarizing a narrow monochromatic light beam having wavelength band within the range of $[\lambda \pm \Delta\lambda/2]$ where $\Delta\lambda$ being a full width at half maximum of the wavelength band , does not exceed $\Delta\lambda \leq$ 1.33 femto-meter, (Δf<500MHz), and diameter D of the beam does not exceed D≤10mm.

[Claim 38]

The method of any one of claims 34 to 37, wherein said polarizing affects attenuation of the light beam by a polarization filtering factor $\alpha_{pol} = 0.5^{*}\pm 0.5^{*}\Delta\alpha_{pol}$ whereby an uncertainty $\Delta\alpha_{pol}$ in the polarization filtering factor $\Delta\alpha_{pol}$ is given by a degree of polarization (DOP) of the light beam after said depolarizing, $\Delta\alpha_{pol}$ = DoP.

[Claim 39]

The method of any one of claims 34 to 38 configured as an all-optical processing method.

[Claim 40]

A method for magnetic field measurements comprising:

providing a light beam for probing a vapor cell to determine a Larmor frequency of precession of atomic vapor therein, whereby said light beam is provided from a remote optical source displaced from said vapor cell, and has a certain predetermined initial intensity I_0 and undetermined initial polarization P_0;

optically processing said light beam, at a location adjacent to said vapor cell to yield said light beam with a certain predetermined intensity I_1 relative to said initial intensity I_0 and certain predetermined polarization state P_1, by:

a. depolarizing said light beam to yield said light beam with a certain intermediate intensity I_{in} and substantially un-polarized polarization state; and

b. subsequent to said depolarizing, polarizing said light beam to yield said predetermined polarization state P_1 and said certain predetermined relative intensity I_1;

subsequent to said optical processing, directing said light beam to pass within the vapor cell and interact with the atomic vapor therein for probing a Larmor frequency of precession thereof; and

detecting at least one of a final polarization state P_2 and a final intensity I_2 of said light beam after the interaction with the atomic vapor after and utilizing said at least one of the final polarization state P_2 and the final intensity I_2 to determine the Larmor frequency of precession of the atomic vapor.

[Claim 41]

The method of claim 40 wherein said optical processing is carried out according to the optical processing method of any one of claims 34 to 39.

[Claim 42]

A spatially distributed magnetometer array comprising a plurality of magnetometers for measuring a magnetic field B in respective vicinities of the magnetometers,

wherein each magnetometer of one or more magnetometers of said plurality comprises:

a. a respective vapor cell of the magnetometer which contains atomic vapor;
b. a respective optical coupler of the magnetometer for optically coupling between a light source providing a respective light beam for said magnetometer, and the vapor cell of said magnetometer;

said spatially distributed network/array comprises:

a. a reference data provider capable of providing data indicative of optical attenuation properties of the respective optical couplers of said one or more magnetometers;
b. one or more intensity adjustment modules, associated respectively with said one or more magnetometers, and respectively capable of adjusting the intensities I_1 of the respective light beams of the magnetometers such that at the entrance to the corresponding vapor cells of the magnetometers the light beams have certain predetermined intensities I_1; and
c. at least one controller connectable to said one or more intensity adjustment modules and configured and operable for operating the one or more intensity adjustment modules according to the optical attenuation properties of the respective optical couplers of the magnetometers associated respectively therewith, to thereby yield said certain predetermined intensities I_1 at the entrance to the vapor cells;

wherein at least one of the light couplers, which is associated with a respective magnetometer of said magnetometers, comprises an optical processor according to any one of claims 29 to 33 configured and operable for receiving the respective light beam of the respective magnetometer, whereby said light beam has a certain initial intensity I_0 and undetermined polarization P_0 and processing said light beam to yield said light beam with a certain predetermined polarization state P_1 and an intensity I_1 relative to said initial intensity I_0 by an attenuation factor α, $I_1 \approx \alpha I_0$.

[Claim 43]

The spatially distributed array of claim 42 wherein the respective optical attenuation properties of the at least some of the light couplers include compensation for the attenuation factor α of the optical processor.

[Claim 44]

The spatially distributed array of claim 42 or 43, wherein the at least one controller **360** is configured and operable for operating the intensity adjustment modules such that the certain predetermined intensities I_1 of the light beams are adjusted to a certain similar predetermined intensity I_1 for a plurality of said magnetometers, thereby providing accurately comparable values of the magnetic field measurements by said plurality of magnetometers.

[Claim 45]

The spatially distributed array of any one of claims 42 to 44 wherein said light couplers include respective optical assemblies, each comprising one or more optical components along a light propagation path from the at least one light source to their respective vapor cells; and wherein the respective optical attenuation properties of the light couplers are associated with the optical attenuation of at least one of the optical components, which has a relatively substantial attenuation.

[Claim 46]

The spatially distributed array of claim 45 wherein optical assemblies of one or more of the light couplers of said magnetometers include respective optical fibers for propagating a respective light beam along at least a part of the light propagation path from the at least one light source to the respective vapor cell; and wherein the respective optical attenuation properties of the at least some of the light couplers, which are provided by said reference data provider, are associated with the attenuation along respective lengths of said fibers.

[Claim 47]

The spatially distributed array of any one of claims 42 to 46 wherein the intensity adjustment modules are each configured and operable for adjusting at least one of said certain initial intensity I_0 and their output intensity I_1 in order to obtain said certain

predetermined intensity I_1 in the respective light beam at the entrance to their respective vapor cells.

[Claim 48]

The spatially distributed array of claim 47 wherein each intensity adjustment module of the intensity adjustment modules includes at least one of the following:

a. a controller connectable to the at least one light source/port for adjusting the output intensity of the light source;
b. an optical amplifier, in the propagation path of its respective light beam, capable of amplifying the intensity of the light beam by an adjustable degree of amplification; and
c. an optical attenuator, in the propagation path of its respective light beam, capable of attenuating the intensity of the light beam by an adjustable degree of attenuation.

[Claim 49]

The spatially distributed network of any one of claims 42 to 48 wherein one or more of said magnetometers are similar magnetometers configured and operable in at least one of the following configurations:

a. all optical magnetometers;
b. Bell-Bloom magnetometers;
c. magnetometers configured and operable according to any one of claims 1 to 28.