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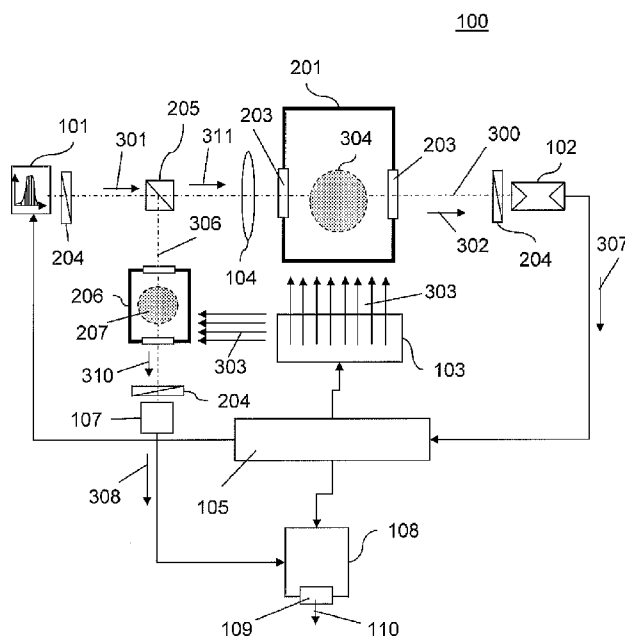


FIG. 5

(57) Abstract: An oxygen concentration measuring device (100) adapted for determining an oxygen concentration of a gas in a sample volume (304) is provided. An optical device is used for irradiating the sample volume (304) containing oxygen with a first light intensity (301). The first light radiation (301) includes radiation at at least two wavelengths close to a given spectral absorption line of oxygen, the spacing of the at least two wavelengths from each other being smaller than the width of the given spectral absorption line of oxygen. A magnetic field generator (103) is adapted for applying a magnetic field (303) at the sample volume (304) and a light detector (102) is adapted for measuring a second light intensity (302) coming from the sample volume (304). The oxygen concentration in the sample volume (304) is determined on the basis of the applied magnetic field (303) and the measured second light intensity (302).

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**OXYGEN CONCENTRATION MEASURING DEVICE AND
METHOD FOR MEASURING OXYGEN**

5 BACKGROUND

The present disclosure generally relates to an oxygen measuring device, and in particular relates to a measuring device which detects an oxygen concentration within a gas sample volume. Furthermore, the present disclosure relates to a method for determining an oxygen concentration in a sample volume containing oxygen.

Gas concentration measurement can be provided by means of light absorption, the absorbed light having an appropriate wavelength or an appropriate range of wavelengths. Oxygen gas is an important gas present e.g. in combustion processes. Residual oxygen detection in combustion processes e.g. yields valuable information for emission monitoring. Furthermore, the measurement of an oxygen concentration in the presence of other gases has abundant applications in the medical field.

In many cases oxygen concentrations present in an ambient gas may be very low such that a sensitive oxygen concentration measuring device is required.

SUMMARY

In view of the above, there is provided an oxygen concentration measuring device according to claim 1, and a method for determining an oxygen concentration in a sample volume according to claim 14.

According to one aspect, the oxygen concentration measuring device is adapted for determining an oxygen concentration of a gas in a sample volume containing oxygen. The oxygen concentration measuring device comprises an optical device adapted for irradiating the sample volume with a first light

radiation having a first light intensity, the optical device comprising a light source adapted for emitting the first light radiation, the first light radiation including radiation at at least two wavelengths close to a given spectral absorption line of oxygen, the spacing of the at least two wavelengths from each other being smaller than the width of the given spectral absorption line of oxygen; a magnetic field generator adapted for applying a magnetic field at the sample volume; a light detector adapted for measuring a second light intensity of a second light radiation coming from the sample volume; and an evaluation unit adapted for determining the oxygen concentration in the sample volume on the basis of the applied magnetic field and the measured second light intensity.

According to another aspect a method for determining an oxygen concentration in a sample volume containing oxygen is provided. The method comprises:

- emitting a first light radiation from a light source towards the sample volume, the first light radiation including radiation at at least two wavelengths close to a given spectral absorption line of oxygen, the spacing of the at least two wavelengths from each other being smaller than the width of the given spectral absorption line of oxygen;
- irradiating the sample volume with the first light radiation;
- applying a magnetic field at the sample volume;
- measuring the intensity of a second light radiation coming from the sample volume; and
- determining the oxygen concentration in the sample volume on the basis of the applied magnetic field and the measured intensity of the second light radiation.

Preferably, the light radiation is visible radiation, i.e. in the wavelength range from 380 nm to 780 nm. Further exemplary embodiments are according to the dependent claims, the description and the accompanying drawings.

DRAWINGS

A full and enabling disclosure, including the best mode thereof, to one of ordinary skill in the art is set forth
5 more particularly in the remainder of the specification, including reference to the accompanying drawings wherein:

Fig. 1 illustrates a schematic block diagram for explaining the principle of an oxygen concentration measurement based on
10 the application of a magnetic field at a sample volume of oxygen to be measured;

Fig. 2 is a block diagram illustrating a control structure for an oxygen concentration measuring device using a lock-in
15 detection technique;

Fig. 3 is a detailed block diagram illustrating an optical set-up of an oxygen concentration measuring device according to a typical embodiment;
20

Fig. 4 is a detailed block diagram illustrating a set-up of an oxygen concentration measuring device having a reference light detector according to another typical embodiment;

25 Fig. 5 is a block diagram illustrating the set-up of an oxygen concentration measuring device according to yet another typical embodiment; and

Fig. 6 shows a flowchart illustrating a method for determining an oxygen concentration in a sample volume according to a typical embodiment.
30

DETAILED DESCRIPTION

35 Reference will now be made in detail to the various exemplary embodiments, one or more examples of which are illustrated in the drawings. Each example is provided by way of explanation and is not meant as a limitation. For example, features

illustrated or described as part of one embodiment can be used alone or in conjunction with other embodiments to yield yet a further embodiment. It is intended that the present disclosure includes such modifications and variations.

5 A number of embodiments will be explained below. In this case, identical structural features are identified by identical reference symbols in the drawings. The structures shown in the drawings are not depicted true to scale but rather serve only for better understanding the embodiments.

10

Fig. 1 is a block diagram illustrating a principle set-up for a measuring device 100 adapted for measuring an oxygen concentration within a sample volume 304. The sample volume 304 can be accessed by an optical sensor system operating in
15 the visible spectral range, typically in a wavelength region from 380 nm to 780 nm, and more preferably in a wavelength range between 755 nm and 765 nm. The sample volume 304 is contained in a sample cell 201 which has windows transmitting the visible light. Light emitted by a light source 101 is
20 transmitted into the sample cell and is partially absorbed by oxygen contained in the sample volume 304. The embodiment can also be carried out with other wavelength radiation, but generally the light source, the sensors and other parts of the optical system are particularly efficient in the visible
25 light spectral range (here, "light" refers to electromagnetic radiation including the IR, visible and UV spectrum, and does not necessarily imply that the radiation is visible).

It is noted here that outside the sample volume 304 and
30 within the sample cell 201 vacuum, nitrogen gas, or another appropriate medium which does not interfere with the oxygen concentration measurement may be provided. Furthermore, a flow of oxygen through the sample cell 201 may be provided such that a continuous measurement of the oxygen
35 concentration in the flow is possible.

A first light intensity 301 is chosen such that it includes at least two wavelengths close to a given spectral absorption

line of oxygen, and that the spacing of the at least two wavelengths from each other is smaller than the width of the given spectral absorption line of oxygen. Here, the width of an absorption line is defined as its half-width, i.e. the distance between the parts of the absorption line at which the absorption is half of the maximum value of the absorption line.

Having the at least two wavelengths close to the given spectral absorption line, compared to only one wavelength, allows for a particularly efficient oxygen concentration measurement for the following reasons:

With only one wavelength close to the given spectral absorption line, there are essentially only two possible outcomes of a measurement: Either the wavelength is within the oxygen absorption line, or not. Hence, only one signal variation can be measured at a very specific wavelength. Hence, the concentration measurement can only rely on one kind of measurement, which makes it less reliable. Further, if the apparatus is not perfectly calibrated such that the wavelengths are slightly out of tune, there may be no signal at all.

On the other hand, with at least two wavelengths close to the given spectral absorption line, there are more available measurement outcomes, depending on whether only one, or both of the wavelengths are within the spectral absorption line. Hence, the measurement signal is influenced in a richer manner and over a wider range of wavelengths when the first radiation wavelength and/or the absorption line wavelength is varied. Thereby, a more stable and contrast-rich signal may be generated over a wider wavelength variation interval.

The signal can further be improved with even more wavelengths being present in the first radiation, e.g. three discrete wavelengths, or a discrete wavelength peak superimposed on a continuous wavelength distribution. It is preferred that at least one of the wavelengths of the first radiation is

present as a discrete peak, because a discrete wavelength peak allows for a good contrast signal as a function of the applied magnetic field. Also, instead of a continuous light emitter, a quasi-continuous light emitter may be used. Here, a quasi-continuous radiation is defined as a radiation the wavelengths of which are spaced from each other by much less (e.g. by less than a fifth) than the width of the oxygen absorption line to be measured.

10 A combination of plural wavelengths can be obtained by providing a combined light source which comprises at least two different light emitters, such that the two wavelengths emerge from mutually different emitters. For example, the light source may comprise any two emitters, each of the emitters being selected from the group consisting of a mercury lamp, a gas laser, a laser diode, a light emitting diode, and a deuterium lamp. In particular, it is possible to obtain a discrete wavelength peak from one emitter superimposed on a continuous wavelength distribution from another emitter, by providing a combined light source which comprises as the one emitter a lamp with a discrete spectrum and as the other emitter a lamp with a continuous spectrum in the frequency region in which the second light intensity is measured. As such an exemplary light source a combined deuterium-mercury lamp is particularly preferred.

If part of the first light intensity 301 is absorbed by oxygen contained in the sample volume 304, a second light intensity 302 which is lower than the first light intensity 301 by an amount which has been absorbed in the sample volume 304 exits the sample volume 304. The second light intensity 302 is detected by a light detector 102 for light which converts the detected light intensity into a measurement signal 307 which is output from the oxygen concentration measuring device and which is a measure for an oxygen concentration contained in the gas within the sample volume 304.

In particular, if the wavelength of the radiation, i.e. the first light intensity 301 is close to an absorption line of a gas to be measured (in this case oxygen), an absorption cross-section for absorbing the incident radiation can be significant. Especially at long wavelengths in the visible light spectral range, absorption of light by oxygen occurs. An example of oxygen absorption lines is the OI line at 762 nm. If a wavelength of the first light intensity 301 is close to this line, an absorption cross-section becomes high.

The term "close to" or "essentially corresponds to" a wavelength means that a respective emission line emitted by the light source 101 and at least one absorption line of oxygen to be measured are overlapping in their respective wavelengths, at least partially. Such an overlapping of lines having wavelengths being close to each other may occur, because an emission line and/or an absorption line do not represent a single wavelength, but exhibit a distribution of wavelengths around a centre wavelength (e.g. the wavelength of 762 nm). Instead of a stationary distribution, the wavelength may also change in time, e.g. due to an influence of a magnetic field. The temporal change (fluctuations or controlled change) of the wavelength can also be considered as leading to a wavelength distribution in the above sense.

This distribution of wavelengths of emission and/or absorption lines results from a line broadening which may e.g. be due to at least one of natural line broadening, Doppler broadening (temperature movement of atoms and/or molecules), Stark broadening (due to an electric field interacting with respective atoms and/or molecules), etc. Thus, a radiation absorption of oxygen not only occurs at a single wavelength of e.g. 762 nm, but in a spectral region in the range of e.g. 755 nm to 765 nm, respectively.

Absorption lines of oxygen occur in different spectral regions. Oxygen, e.g. has absorption lines corresponding to the emission lines of a mercury lamp. Thus, a mercury lamp may be provided as the light source 101. Furthermore, a laser

emitting light which may be tuneable and may be adjusted such that its emission wavelength corresponds to an appropriate spectral absorption line of oxygen is appropriate for the oxygen concentration measurement. In general the wavelength
5 range in which an absorption may occur is described by the half-width of an absorption line.

An irradiation of the sample volume 304 by a first light intensity 301 which includes visible light has the advantage
10 that, albeit an absorption cross-section defining the amount of radiation absorption is lower than in the UV spectral region, the light sources emitting visible light, such as laser diodes, gas lasers, light emitting diodes (LED), etc., are very intense in output radiation and/or very stable in
15 output wavelength. The spectral region of visible light typically includes wavelengths between 380 nm and 780 nm.

A magnetic field 303 is applied at the sample volume 304 via a lower part of the sample cell 201 (shown in Fig. 1), or by
20 using a solenoid coil the centre of which is the sample cell 201. Under the influence of this magnetic field 303 an oxygen absorption line may split into sets of components of shorter and longer wavelengths as compared to a centre wavelength obtained with no magnetic field 303. This line splitting is
25 in accordance with the Zeeman effect which is known as such to the skilled person.

The magnetic field lines may be parallel to the propagation direction of the first light intensity 301, albeit not shown
30 in Fig. 1. According to a typical embodiment, the absorption line is split into two separate lines by the effect of the applied magnetic field 303. In accordance with the Zeeman effect, one of these lines is right-handed polarized, whereas the other of these two lines is left-handed polarized. In
35 order to distinguish between the intensities of these two polarized lines, a polarization analyzer 305 is provided in the exit path, i.e. in the radiation path between the sample volume 304 and the light detector 102. The light source 101 may emit polarized radiation or the light emitted by the

light source may be polarized by means of a polarizing element 204.

As the magnetic field 303 is generated by a magnetic field generator 103, the magnetic field 303 may be switched on and off periodically. This results in the advantage that a Zeeman splitting of an absorption line of oxygen may be present (magnetic field 303 switched on) or not present (magnetic field 303 switched off). Thus, the relation between the wavelength of the first light intensity 301 incident onto the sample volume 304 and the wavelength of the absorption line of oxygen to be measured varies in accordance with the presence of the magnetic field 303. Furthermore, the second light intensity varies in accordance with the variation of the magnetic field 303, because an absorption of the first light intensity 301 is dependent on a wavelength difference between the incident wavelength and the absorption wavelength of oxygen.

Advantageously the oxygen concentration within the sample volume 304 may be determined on the basis of different measurement procedures. The underlying principle of a first kind of measurement procedure is a comparison of at least one measurement where an absorption of light radiation by oxygen occurs, with at least one measurement wherein an absorption of this light radiation is decreased or is not present at all. Then, by evaluating the difference in absorption, i.e. the difference between both measurements, a high-contrast signal for the oxygen concentration can be obtained, because other effects on the signal cancel each other in the difference signal.

According to a typical embodiment described herein below a wavelength of the first light radiation which is emitted by the light source 101 may be held essentially constant throughout the measurement, whereas the oxygen absorption line is Zeeman-shifted by the magnetic field 303 during at least one measurement. Then, during at least one measurement, the magnetic field may be tuned close to an "absorption"

value such that the Zeeman shift causes the oxygen absorption line to essentially coincide or overlap with the wavelength of the first light radiation. During another measurement, the absence of such a Zeeman shift (absence of the magnetic field
5 303 or magnetic field 303 tuned away from the "absorption" value) may cause the oxygen absorption line not to coincide or overlap with the wavelength of the first light radiation. Due to the change in absorption between these measurements, the second light intensity incident onto the light detector
10 varies in accordance with the magnetic field variation. Thus, resulting variations in the measurement signal 307 depend on a radiation absorption by oxygen and thus on the oxygen concentration in the sample volume 304.

15 If known oxygen concentrations in the sample volume 304 can be provided and the corresponding variations in the measurement signal 307 are detected, the oxygen concentration measuring device 100 can be calibrated. This calibration can be provided as a table or function which relates measurement
20 signal variations to corresponding oxygen concentrations within the sample volume 304.

According to another typical embodiment the light source 101 may be provided as a gas discharge lamp, e.g. a mercury lamp,
25 a deuterium lamp, or a combination thereof, such as a combined deuterium-mercury lamp. Instead of or in addition to applying a magnetic field at the sample volume, a magnetic field may be applied at the gas discharge of the light source 101. A Zeeman shift is provided by the magnetic field applied
30 at the light source 101 and this Zeeman shift may cause at least one wavelength of the first light radiation emitted by the gas discharge lamp to essentially coincide with the oxygen absorption line. Furthermore, an absence of the magnetic field, i.e. no Zeeman shift, may cause the
35 wavelength of the first light radiation not to coincide with the oxygen absorption line, or vice versa. The modified absorption with and without magnetic field again results in variations of the measurement signal 307 and these variations are a function of the oxygen concentration in the sample

volume 304. Again, known oxygen concentrations in the sample volume 304 can be provided and corresponding variations in the measurement signal 307 can be monitored such that a calibration of the entire measuring device may be carried out
5 as described above.

Furthermore, and in accordance with yet another typical embodiment, at least one polarization state of the second light radiation incident onto the light detector 102 may be
10 analysed. In this case the magnetic field applied at the sample volume 304 or at the light source 101 is maintained at a constant value which is appropriate for providing a sufficient Zeeman shift. Due to the Zeeman effect, typically the polarization states of the components upshifted and
15 downshifted in wavelength are different with respect to each other. E.g., the upshifted and downshifted components exhibit circular polarizations of opposite handedness. A wavelength of the first light radiation which is emitted by the light source 101 may coincide with the upshifted component of the
20 oxygen absorption line whereas the downshifted component only minimally coincides with the oxygen absorption line, or vice versa. Due to the modified absorption of incident first light intensity at the upshifted and downshifted components, respectively, the second light intensity incident onto the
25 light detector varies accordingly. Thus resulting variations in the measurement signal 307 outputted from the light detector 102 may be utilised to evaluate the oxygen concentration in the sample volume 304 in a similar manner as described above with respect to the variations of the
30 magnetic field applied at the sample volume 304 and/or at the light source 101. A polarizing element 204 may then be used in the propagation path of the second light radiation coming from the sample volume 304 in order to alternately select the two different polarization states mentioned above, i.e.
35 circular polarizations of opposite handedness (a left circularly or a right circularly polarization state) are selected.

As a quantity characterizing the difference in absorption (here exemplified by the difference between the measured intensities of the left and the right circularly second light radiation, but any other two measurement values may be used instead), the following quantities may be used e.g.: the numerical difference between the measured intensities of the left and the right circularly second light radiation; the ratio of the measured left and right circularly polarized second radiation intensities; and/or the relative difference, i.e. numerical difference as above, divided by the sum of the left and the right circularly second light radiation.

Also, more than two different kinds of measurements can be compared in order to obtain even more signal contrast. For example, the absorption can be measured while the magnetic field is changed continuously between two limiting values, and hence the absorption spectrum can be measured as a continuous function of the magnetic field. In this case, the distribution of absorption values is characterized by statistical quantities (mean variance, higher-order variances). This allows a particularly stable signal.

Preferably, each of the different kinds of measurements are performed more than once, and more preferably they are performed periodically. This allows obtaining an even more stable signal, because signal fluctuations are statistically averaged. The periodical measurement can e.g. be performed using a lock-in technique, such as described e.g. further below. An evaluation of the measurement signals by means of an evaluation unit (described herein below with respect to Figs. 2-5) may be performed by adjusting the wavelength of the light source 101 such that it coincides with an oxygen absorption wavelength in such a way that the Zeeman-effect induced shifts of the oxygen absorption line for left and right circularly polarized radiation cause a difference in absorption for the measured left and right circularly polarized waves. Then, both measurement signals can be evaluated, e.g. by forming their ratio or forming their difference over their sum, and can then be used as a highly

sensitive measure of the oxygen concentration. For this purpose, in addition, a calibration of the evaluated signal versus an actual oxygen concentration may be carried out, e.g. a priori for a given measurement setup, or continuously or intermittently during operation by reference measurements with a reference oxygen cell 206, as indicated in Fig. 5 herein below. In addition, the relevant spectral light intensity which exits the reference oxygen cell can be monitored and can be used for signal evaluation.

In order to increase a signal-to-noise ratio a lock-in detection mode may be employed which is described herein below with reference to Fig. 2. An oxygen concentration in the sample volume 304 may then be determined on the basis of changes in the second light intensity 302 if the intensity of the magnetic field 303 is varied, i.e. switched on and off.

Furthermore, it is possible to provide a sinusoidal modulation of the magnetic field. The sinusoidal modulation has the advantage that the design of the magnetic field generator is facilitated and that a frequency for changing the magnetic field 303 may easily be adjusted by means of a frequency generator (not shown).

Moreover, the magnetic field may be periodically reversed in polarity. This kind of polarity change has the strongest influence on the Zeeman line splitting such that the polarization analyzer 305 may alternately select the set of the longer or upshifted components or the set of the shorter or down-shifted components and pass the selected set to the light detector 102.

Thus, by changing the intensity of the magnetic field 303 by means of the magnetic field generator 103, the measurement signal 307 varies in accordance with the variation of the magnetic field 303. This variation is due to the fact that a Zeeman shift of the oxygen absorption line causes a variation in the absorption such that the second light intensity 302 is varied while the first light intensity 301 is kept at a constant incident wavelength and intensity.

Fig. 2 is a block diagram illustrating a lock-in signal detection technique for obtaining the measurement signal 307 described with respect to Fig. 1. As shown in Fig. 2, a control unit 105 is provided which generates a modulation signal 312 for controlling the magnetic field generator 103. The control unit 105 receives the measurement signal 307 described herein above with respect to Fig. 1. The light source 101 emits the first light intensity 301 towards the sample volume 304 within the sample cell 201. As explained with respect to Fig. 1, a modulated second light intensity 302 is obtained, if the magnetic field 303 is modulated. Thus, the control unit 105 is capable of correlating the frequency of the modulation signal 312 to the frequency of the measurement signal 307 in order to provide a phase sensitive detection.

The control unit 105 includes a frequency generator unit 106 adapted for generating the modulation signal 312 provided for the magnetic field generator 103. It is noted here that the modulation signal 312 may include a sinusoidal modulation, an on/off-switching or any other modulation known to the skilled person. Furthermore, the control unit 105 includes a phase comparator unit 202 for comparing phases of two input signals. One input signal of the phase comparator unit 202 is a frequency signal 314 provided by the frequency generator unit 106. The frequency signal 314 corresponds to the modulation signal 312 with respect to its frequency.

The second signal input into the phase comparator unit 202 is the measurement signal 307 output from the light detector 102. The phase comparator unit 202 compares the phases of the two input signals and outputs a lock-in signal 313 which is based on a correlation of the two input signals of the phase comparator unit. The control unit 105 thus provides an enhancement of the signal-to-noise ratio for the oxygen concentration measurement using the oxygen concentration measuring device 100 because only components of the measurement signal 307 which have a fixed phase relation with respect to the modulation signal 312 are amplified and output

as the lock-in signal. Other contributions in the measurement signal 307 which are not correlated to the frequency and phase of the modulation signal 312, e.g. noise and other interference, are cancelled out by phase comparator unit 202.

5

The lock-in signal 313 is input into an evaluation unit 108 which evaluates, on the basis of the lock-in signal 313, an output signal indicating the amount of absorption in the sample volume 304. The output signal 110 is output via an output unit 109. The output signal 110 is a direct measure of the oxygen concentration within the sample volume 304, because it reflects an absorption of the first light intensity 301 correlated to the magnetic field variation (magnetic field modulation) 303 provided by the magnetic field generator 103.

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Fig. 3 is a more detailed block diagram of an oxygen concentration measuring device 100 according to a typical embodiment. It is noted here that in Figs. 3, 4 and 5 the dotted lines correspond to optical paths, wherein the solid lines having an arrow correspond to electrical paths. The parallel arrows indicated by a reference numeral 303 correspond to a magnetic field 303 which may be oriented parallel to the propagation direction of the first light intensity 301 and/or the second light intensity 302.

25

The first light intensity 301 emitted from the light source 101 is directed onto an optical focussing unit 104, such as a lens, adapted for directing and focussing the first light intensity right into the centre of the sample volume 304 contained in the sample cell 201. After the first light intensity 301 has been partially absorbed by the oxygen contained in the sample volume 304, a second light intensity 302 which is lower than the first light intensity 301 by an amount which has been absorbed in the sample volume 304 exits the sample volume 304 and propagates towards the light detector 102 via the polarization analyzer 305 (described herein above with respect to Fig. 1).

35

Fig. 4 is a detailed diagram of an oxygen concentration measuring device according to another typical embodiment. It is noted here that parts or components which have been described already with respect to previous figures are not repeated in the description and in the following figures in order to avoid a redundant description.

As shown in Fig. 4, the control unit 105 is used to control the magnetic field generator 103 and the light source 101. The light source 101 may be switched on and off in accordance with required operating conditions. In contrast to the embodiment shown with respect to Fig. 3 herein above, the embodiment of Fig. 4 includes a reference light detector 102 which receives a reference light intensity in order to determine an oxygen concentration in the sample volume 304 on the basis of a reference signal 308 which is provided by the reference light detector 102.

In the following, the generation of the reference signal 308 will be described in detail. The optical set-up of the oxygen concentration measuring device 100 according to Fig. 4 consists of two optical paths, i.e. an optical axis 300 which connects the light source 101 via the sample volume 304 to the light detector 102.

A second optical axis, i.e. a reference detector optical axis 306, is provided in an orientation perpendicular to the optical axis 300. A portion of the first light intensity 301 is directed to a reference cell 206 which contains a known oxygen concentration within a reference volume 207. The portion of the first light intensity 306 is directed along the reference detector optical axis 306 via a polarization analyser 305 towards the reference light detector 107. The reference light detector 107 receives a reference light intensity 310 in accordance with absorption processes which take place in the reference volume 207 having a known and fixed oxygen concentration. Except that the oxygen concentration in the reference cell 206 is known, the processes of Zeeman splitting and radiation absorption are identical or similar to the processes which take place in the sample cell 201. To this end, the magnetic field generator

103 provides a magnetic field 303 not only for the sample cell 201, but also for the reference cell 206. Thus, both the sample volume 304 and the reference volume 207 are penetrated by the modulated magnetic field 303.

5

An output signal of the reference light detector 107 is provided as a reference signal 308 for the evaluation unit 108. The evaluation unit 108 may then evaluate the final output signal 110, i.e. an oxygen concentration in the sample
10 volume 304 of the sample cell 201, on the basis of both the measurement signal 307 output from the light detector 102 and the reference signal 308 output from the reference light detector 107.

15 Furthermore, the evaluation unit 108 is adapted for receiving this measured reference signal 308 indicative of the oxygen concentration in the reference cell 206 such that the oxygen concentration in the sample volume 304 may be determined on the basis of the reference signal 308.

20

According to another typical embodiment a calibration curve may be provided which can be stored in a memory of the evaluation unit 108. Such kind of calibration curve may be obtained from measurements with a known oxygen concentration
25 in the sample volume 304. A curve of the measurement signal 307 may then be acquired as a function of a varying oxygen concentration in the sample volume 304 and may be stored as the calibration curve.

30 For measuring the oxygen concentration, the light source 101 emits a radiation preferably in the wavelength range between 380 nm and 780 nm, i.e. in the visible spectral region, preferably in the range between 755 nm and 765 nm, and more preferably has a wavelength of about 762 nm. The term "about
35 762 nm" means that the wavelength of the light source 101 is near an absorption line of oxygen to be measured. Near an absorption line of oxygen means that the absorption line of oxygen and the emitting line of the light source 101 are close enough in wavelength such that the line profiles which
40 are defined by the half-widths of the respective lines overlap each other.

The light source 101 may be provided as at least one of a mercury lamp, a diode laser, a narrow band diode laser, a gas laser, a light emitting diode, and a deuterium lamp.

5 Advantageously the deuterium lamp may contain mercury (Hg) such that emission lines of Hg are excited and the light source 101 emits spectral lines of the mercury spectrum. This results in a more efficient absorption of the light radiation emitted by the light source 101, because some of the Hg
10 emission lines coincide, at least partially, with absorption lines of oxygen.

The control unit 105 is adapted for controlling the light source 101. Such a control may include the switching of the
15 light source 101, a modulation in light intensity, etc.

Furthermore, it is possible, albeit not shown in Fig. 4, that the reference light detector 107 directly measures a portion of the first light intensity 301 such as to provide a
20 reference signal for the light intensity of the light source 101. In this case the reference cell 206 is not present in the reference detector optical axis 306. An advantage of such a configuration is that even if the light intensity of the light source 101 varies, and in consequence the light
25 intensity measured at the light detector 102 varies even for a constant oxygen concentration in the sample volume 304, this light intensity variation of the light source 101 may be taken into account and its influence on the output signal 110 may be eliminated.

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Fig. 5 is a detailed block diagram of an oxygen concentration measuring device 100 according to yet another typical embodiment. The oxygen concentration measuring device 100 according to Fig. 5 includes, in addition to the oxygen
35 concentration measuring device 100 shown in Figs. 3 and 4, two polarizing elements 204. One polarizing element 204 is arranged at the optical exit of the light source 101, wherein the other polarizing element 204 is arranged in front of the light detector 102.

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By using both polarizing elements 204, it is possible to irradiate the sample volume 304 by means of a polarized first light intensity 301 and to detect a polarized second light intensity 302 in accordance with the setting of both polarizing elements 204. When the first light intensity 301 has a circular polarization, then the up-shifted and down-shifted Zeeman components in the second light intensity 302 have different polarization directions, i.e. a left-handed polarization for one component and a right-handed polarization for the other component. Thus it is possible, by using the second polarizing element 204 arranged in front of the light detector 102 that one of the two components is filtered out. In combination with a varying magnetic field 303, it is then possible to scan an oxygen absorption line over the central wavelength which is provided in the first light intensity 301. Except for the polarizing elements 204, the arrangement of the oxygen concentration measuring device 100 is similar to the concentration measuring device 100 shown in Fig. 4.

According to yet another typical embodiment, the magnetic field generator is a first magnetic field generator. Furthermore, a second magnetic field generator is provided which is adapted for applying a magnetic field at the sample volume 304. The first and second magnetic field generators are adapted for applying mutually perpendicular magnetic fields. This results in a polarized second light intensity 302 in directions such that a signal-to-noise ratio may be increased by gating the output using a fixed polarizing element 204 arranged in front of the light detector 102.

Fig. 6 is a flowchart illustrating a method for determining an oxygen concentration in a sample volume according to a typical embodiment. At step S1, the procedure starts. At step S2, a first light intensity is emitted towards the sample volume. The light radiation includes at least one wavelength which is close to a spectral absorption line of oxygen. Then the procedure advances to a step S3 wherein the sample volume which contains an oxygen concentration to be measured is irradiated with the first light intensity.

At step S4, a magnetic field is applied at the sample volume. The procedure advances to step S5 and an intensity of a second radiation coming from the sample volume is measured. The second light intensity is different from the first light
5 intensity because a part of the first light intensity is absorbed by oxygen contained in the sample cell. From the difference intensity between the first light intensity and the second light intensity, an oxygen concentration in the sample volume is determined at step S6. Then the procedure
10 advances to step S7 where it is ended.

The magnetic field which is applied at the step S4 may be modulated sinusoidally between a minimum magnetic field value and a maximum magnetic field value in order to obtain an
15 appropriate Zeeman splitting of the spectral absorption line of oxygen which is close to the wavelength of the light radiation incident into the sample volume. Furthermore, it is possible to change or reverse a polarity of the magnetic field which is applied at the sample volume. Moreover, the
20 magnetic field may be changed periodically between an essentially constant on-value in an on-state and a zero magnetic field value in an off-state.

A magnetic field may be applied at the light source 101 in
25 addition to or instead of applying the magnetic field at the sample volume 304. If the magnetic field is applied at the light source 101, then emission lines of the light source are Zeeman-shifted resulting in a similar oxygen concentration detection mode as the one described above. In addition the
30 application of a magnetic field at the light source 101 may provide a fine-tuning of at least one emission wavelength of the light source 101.

On the basis of the provided Zeeman-shift more than one spectral absorption line of oxygen may be probed such that a
35 vibrational molecule temperature of oxygen (oxygen molecule) and/or a rotational molecule temperature of oxygen (oxygen molecule) may be determined by probing respective vibrational oxygen molecule bands and/or rotational oxygen molecule bands, respectively. Such kind of probing may include a scan
40 across at least a part of a rotational or vibrational oxygen spectrum (ro-vibrational spectrum) such that at least two

absorption lines of an oxygen molecule are involved in the absorption process described herein above. If two or more absorption lines are probed or "scanned" (e.g. a rotational and/or a vibrational band of oxygen) then temperature
5 information may be obtained in addition to species density (oxygen concentration) information. In an oxygen molecule, the absorption lines of a rotational band are closer to each other as compared to the absorption lines in a vibrational band. Thus, a Zeeman shift for probing vibrational molecule
10 bands has to be larger than a Zeeman shift for probing rotational molecule bands.

Application fields of the oxygen concentration measuring device 100 according to any one of the described embodiments
15 include industrial control devices where a concentration of oxygen has to be measured and/or monitored. Furthermore, in environmental monitoring and medical monitoring the oxygen concentration is a critical issue in many cases. Furthermore, combustion processes for which a specific oxygen
20 concentration has to be provided can be monitored using the oxygen concentration measuring device 100 according to any one of the embodiments described above.

The invention has been described on the basis of embodiments
25 which are shown in the appended drawings and from which further advantages and modifications emerge. However, the disclosure is not restricted to the embodiments described in concrete terms, but rather can be modified and varied in a suitable manner. It lies within the scope to combine
30 individual features and combinations of features of one embodiment with features and combinations of features of another embodiment in a suitable manner in order to arrive at further embodiments.

35 It will be apparent to those skilled in the art, based upon the teachings herein, that changes and modifications may be made without departing from the disclosure and its broader aspects. That is, all examples set forth herein above are intended to be exemplary and non-limiting.

REFERENCE NUMERALS

- 100 oxygen concentration measuring device
- 101 light source
- 102 light detector
- 103 magnetic field generator
- 104 optical focussing unit
- 105 control unit
- 106 frequency generator unit
- 107 reference light detector
- 108 evaluation unit
- 109 output unit
- 110 output signal
- 201 sample cell
- 202 phase comparator unit
- 203 window
- 204 polarizing element
- 205 beam splitter unit
- 206 reference cell
- 207 reference volume
- 300 optical axis
- 301 first light intensity
- 302 second light intensity
- 303 magnetic field
- 304 sample volume
- 305 polarization analyser
- 306 reference detector optical axis
- 307 measurement signal
- 308 reference signal
- 309 oxygen concentration signal
- 310 reference light intensity
- 311 incident first light intensity
- 312 modulation signal
- 313 lock-in signal
- 314 frequency signal

CLAIMS

1. An oxygen concentration measuring device (100) adapted for determining an oxygen concentration of a gas in a sample volume (304) containing oxygen, the oxygen concentration measuring device (100) comprising:

an optical device adapted for irradiating the sample volume (304) with a first light radiation (301) having a first light intensity, the optical device comprising a light source (101) adapted for emitting the first light radiation (301), the first light radiation (301) including radiation at at least two wavelengths close to a given spectral absorption line of oxygen, the spacing of the at least two wavelengths from each other being smaller than the width of the given spectral absorption line of oxygen;

a magnetic field generator (103) adapted for applying a magnetic field (303) at the sample volume (304);

a light detector (102) adapted for measuring a second light intensity of a second light radiation (302) coming from the sample volume (304); and

an evaluation unit (108) adapted for determining the oxygen concentration in the sample volume (304) on the basis of the applied magnetic field (303) and the measured second light intensity (302).

2. The oxygen concentration measuring device (100) according to claim 1, wherein the light source (101) is adapted for tuning the at least two wavelengths of the first light radiation such as to shift the wavelengths by an amount greater than the width of the oxygen spectral absorption line.

3. The oxygen concentration measuring device (100) according to claim 1 or 2, wherein the light source (101) comprises a plurality of light emitters, the light emitters preferably being adapted for emitting light at mutually different wavelengths, more preferably such that the at least two

wavelengths are emitted from mutually different ones of the plurality of light emitters.

4. The oxygen concentration measuring device (100) according to any one of the preceding claims, wherein the light radiation emitted by the light emitter of the light source (101) has one of a right circularly polarization state, a left circularly polarization state and a linear polarization state, or has at least two different ones of these polarization states.

5. The oxygen concentration measuring device (100) according to any one of the preceding claims, wherein the first light radiation (301) has a discrete wavelength distribution including the at least one, preferably at least two, of the wavelengths close to the given oxygen spectral absorption line as local emission maximum or maxima.

6. The oxygen concentration measuring device (100) according to any one of the preceding claims, wherein the first light radiation (301) has a continuous or quasi-continuous wavelength distribution in a frequency range including the at least two wavelengths close to the given oxygen spectral absorption line.

7. The oxygen concentration measuring device (100) according to claim 6, wherein the frequency range includes at least two oxygen spectral absorption lines.

8. The oxygen concentration measuring device (100) according to any one of the preceding claims, further comprising a reference cell (206) which contains oxygen of a reference concentration, and wherein the evaluation unit (108) is adapted for receiving a measured oxygen concentration reference signal (308) indicative of the oxygen concentration in the reference cell (206), and for determining the oxygen concentration in the sample volume (304) on the basis of the oxygen concentration reference signal (308).

9. The oxygen concentration measuring device (100) according to any one of the preceding claims, wherein the light source (101) comprises at least one of a mercury lamp, a gas laser emitting at least two spectral emission lines, an array of at least two laser diodes operating at different output wavelengths, a light emitting diode, a deuterium lamp, or a combination thereof, in particular a combination of a lamp with a discrete spectrum and a lamp with a continuous spectrum in the frequency region in which the second light intensity is measured, such as a combined deuterium-mercury lamp.

10. The oxygen concentration measuring device (100) according to any one of the preceding claims, wherein a reference light detector (102) is adapted for measuring an intensity of at least a portion of the first radiation as a light reference signal (308), and wherein the evaluation unit (108) is adapted for receiving the light reference signal (308) from the reference light detector (102) and for using the light reference signal (308) for the determination of the oxygen concentration.

11. The oxygen concentration measuring device (100) according to any one of the preceding claims, wherein the optical device further comprises a polarizing element (204) adapted for providing polarized first light radiation (301) in the sample volume (304).

12. The oxygen concentration measuring device (100) according to any one of the preceding claims, in which the magnetic field generator (103) is a first magnetic field generator (103), further comprising a second magnetic field generator (103) adapted for applying a magnetic field (303) at the sample volume (304), wherein the first and second magnetic field generators (103) are adapted for applying mutually perpendicular magnetic fields (303).

13. The oxygen concentration measuring device (100) according to any one of the preceding claims, wherein the first light radiation is visible radiation, preferably in a wavelength

range between 380 nm and 780 nm, and more preferably in a wavelength range between 755 nm and 765 nm.

14. A method for determining an oxygen concentration in a sample volume (304) containing oxygen, the method comprising:

5 emitting a first light radiation from a light source (101) towards the sample volume (304), the first light radiation (301) including radiation at at least two wavelengths close to a given spectral absorption line of oxygen, the spacing of the at least two wavelengths from each other being smaller
10 than the width of the given spectral absorption line of oxygen;

irradiating the sample volume (304) with the first light radiation;

applying a magnetic field (303) at the sample volume (304);

15 measuring the intensity of a second light radiation coming from the sample volume (304); and

determining the oxygen concentration in the sample volume (304) on the basis of the applied magnetic field (303) and the measured intensity of the second light radiation.

20 15. The method according to claim 14, wherein a magnetic field is applied at the light source (101), such that emission lines of the light source (101) are shifted with respect to at least one oxygen spectral absorption line.

25 16. The method according to claim 14 or 15, wherein the magnetic field (303) applied at the sample volume and/or the magnetic field applied at the light source (101) is modified by means of an essentially sinusoidal modulation between a minimum magnetic field value and a maximum magnetic field value, a periodic magnetic field polarity reversal, and/or a
30 periodic switching between an essentially constant on-value in an on-state and a zero magnetic field value in an off-state, while measuring the second light radiation intensity.

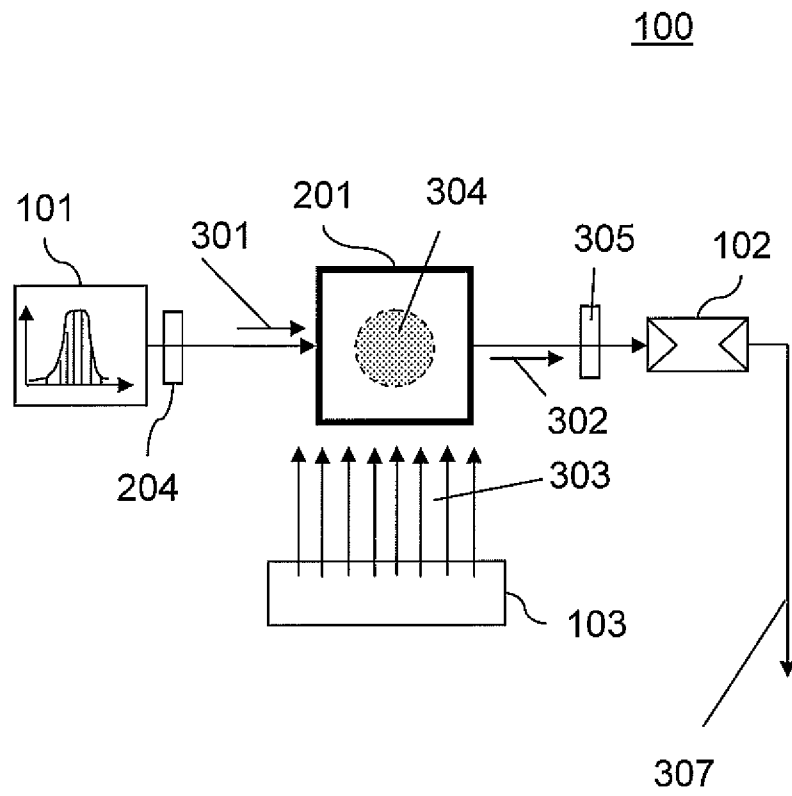
17. The method according to any one of claims 14 to 16, wherein a vibrational molecular temperature of oxygen is determined by probing vibrational oxygen molecular bands.

18. The method according to any one of claims 14 to 17,
5 wherein a rotational molecular temperature of oxygen is determined by probing rotational oxygen molecular bands.

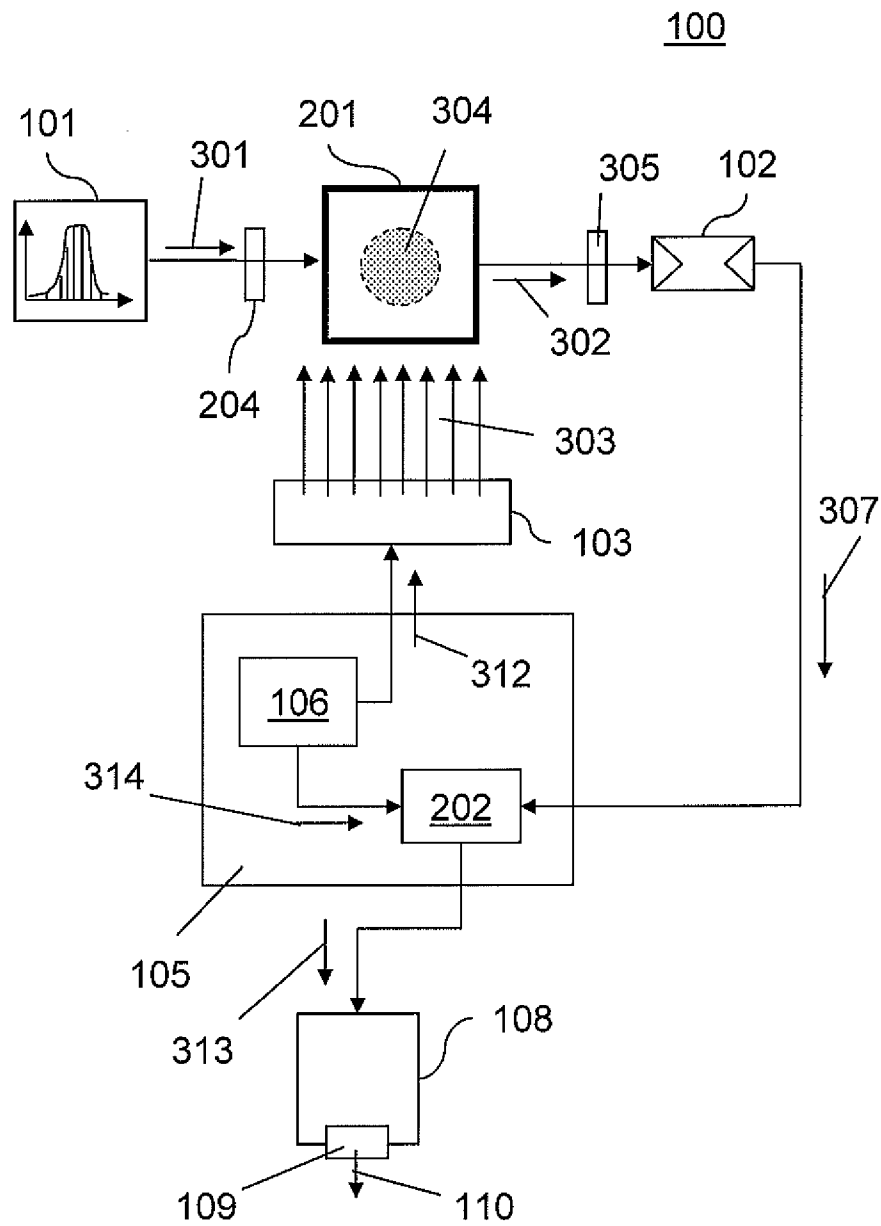
19. The method according to any one of claims 14 to 18, wherein the intensities of the left circularly second light radiation and of the right circularly second light radiation
10 are measured, and the oxygen concentration in the sample volume (304) is determined on the basis of the measured intensities and/or on the basis of the ratio of the measured left and right circularly polarized second radiation intensities, and/or on the basis of their difference,
15 preferably divided by their sum.

20. The method in accordance with any one of claims 14 to 19, wherein the first light radiation is visible radiation.

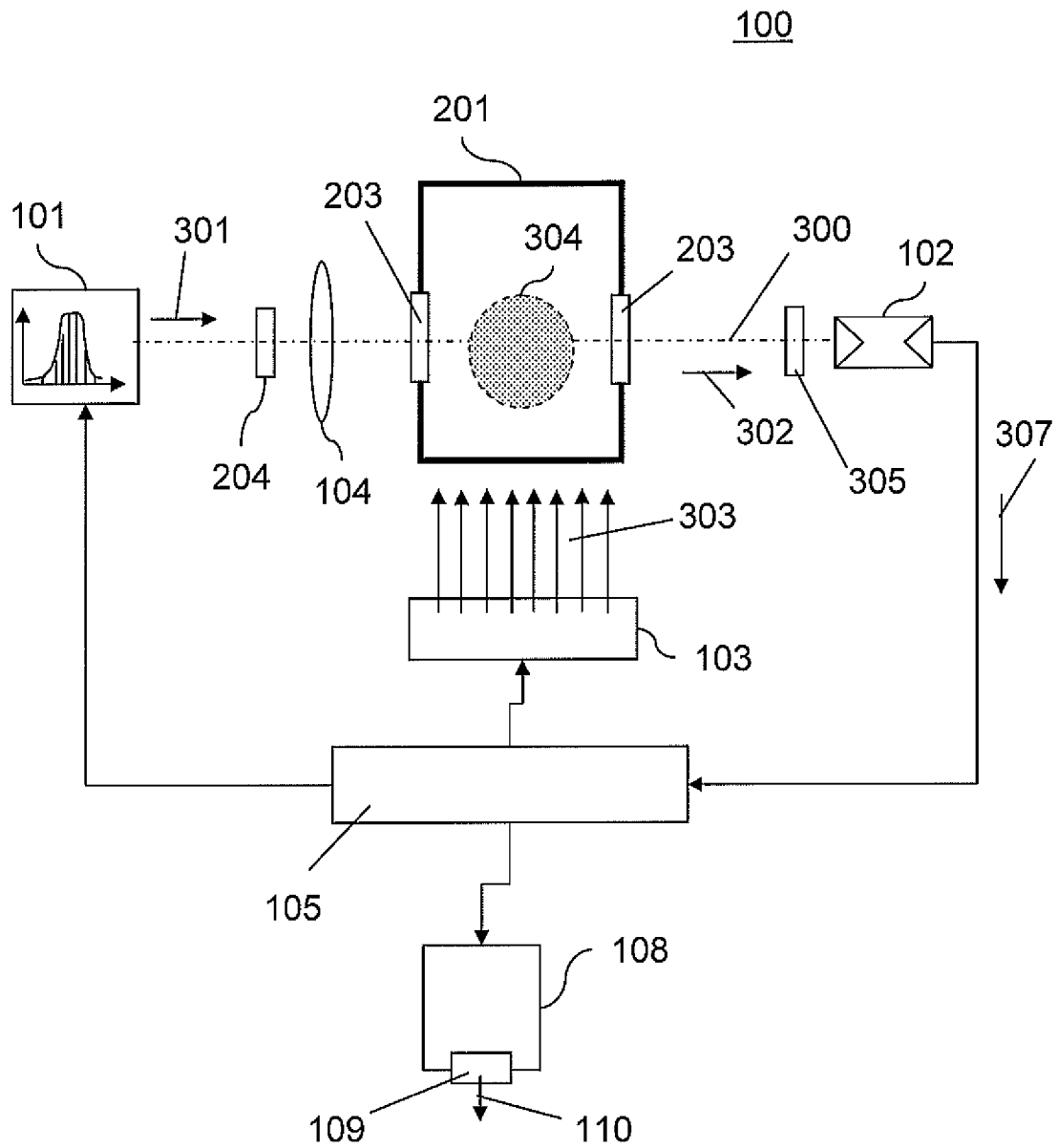
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**FIG. 1**

2/6

**FIG. 2**

3/6

**FIG. 3**

4/6

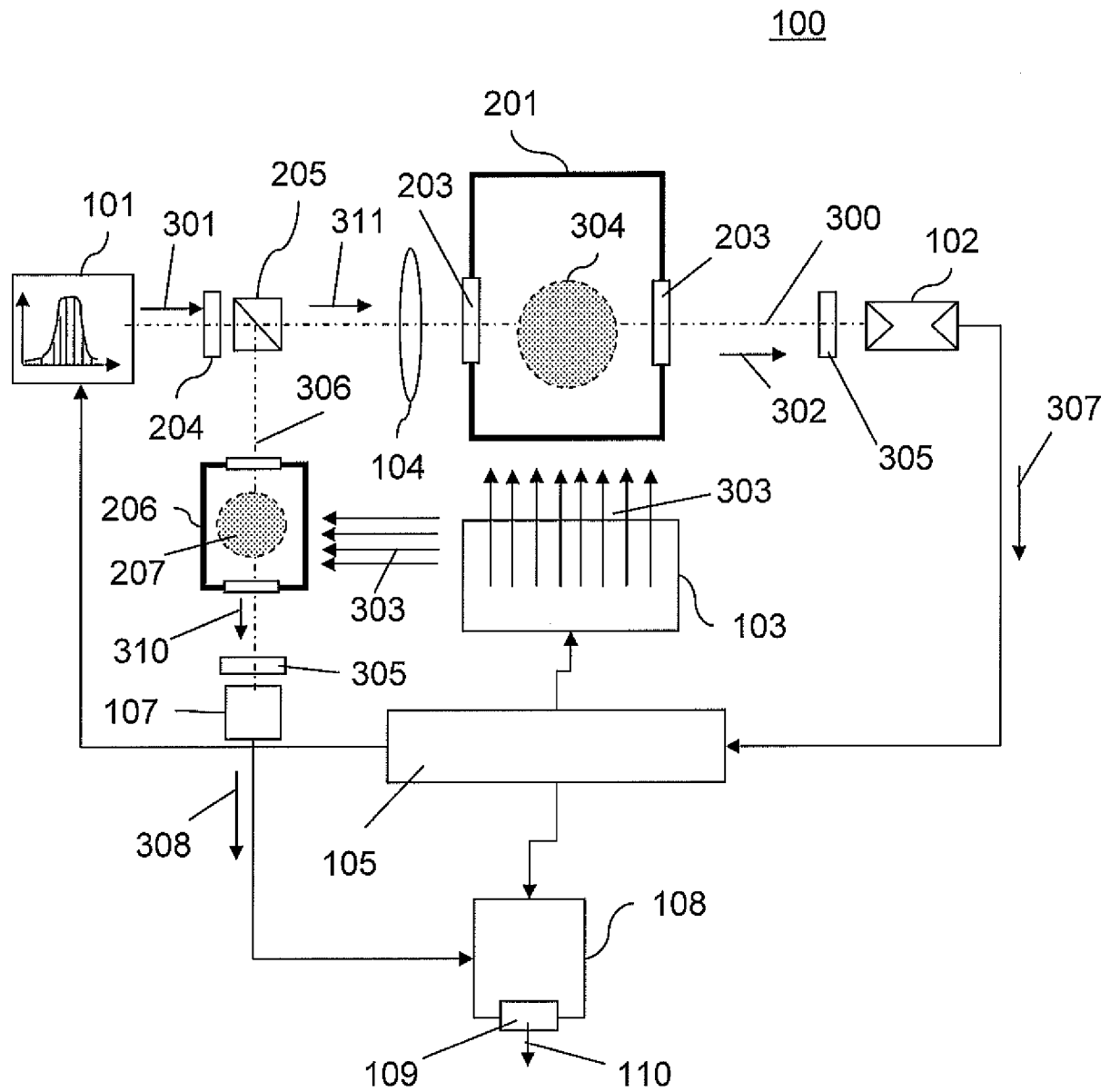
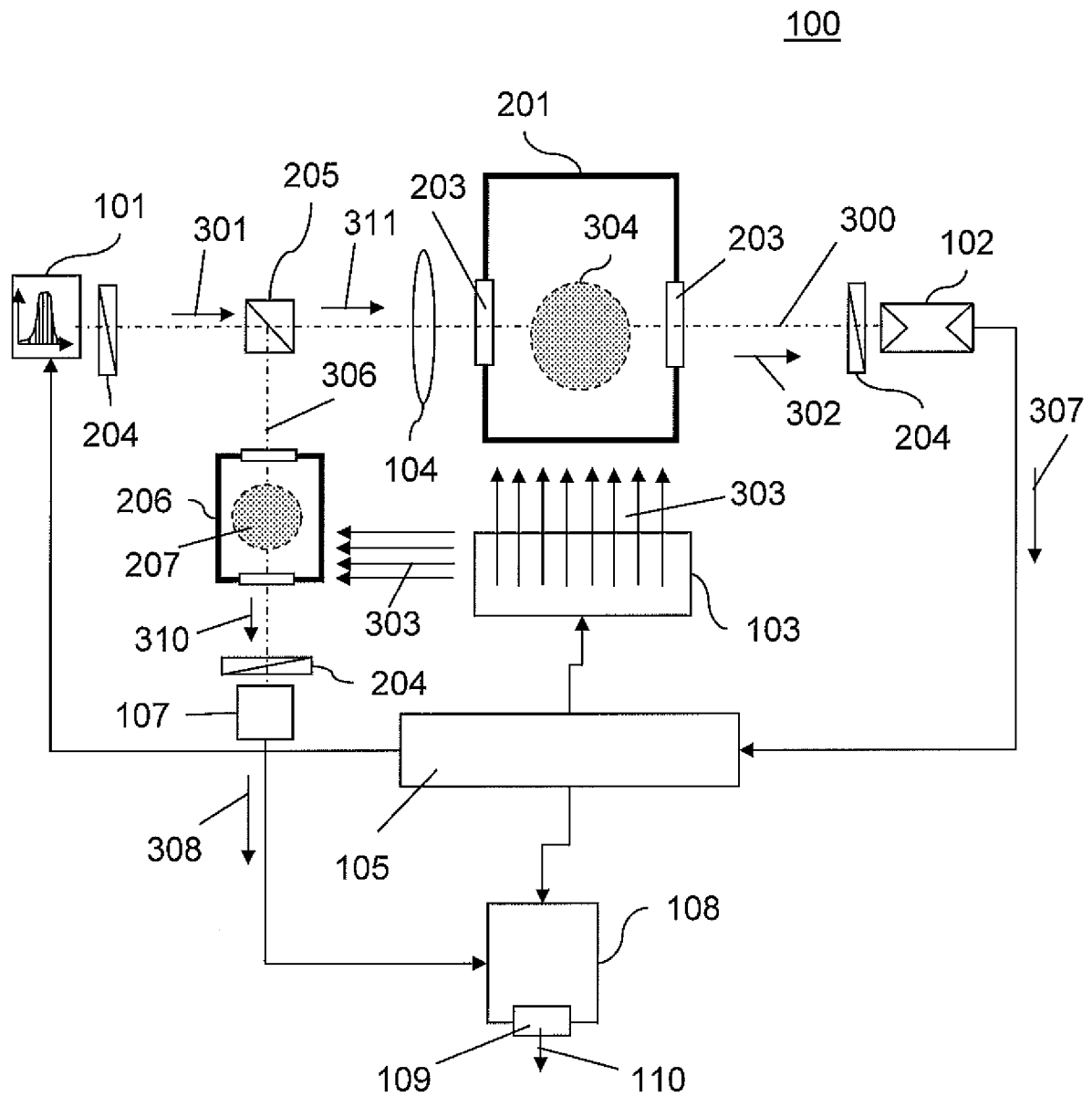
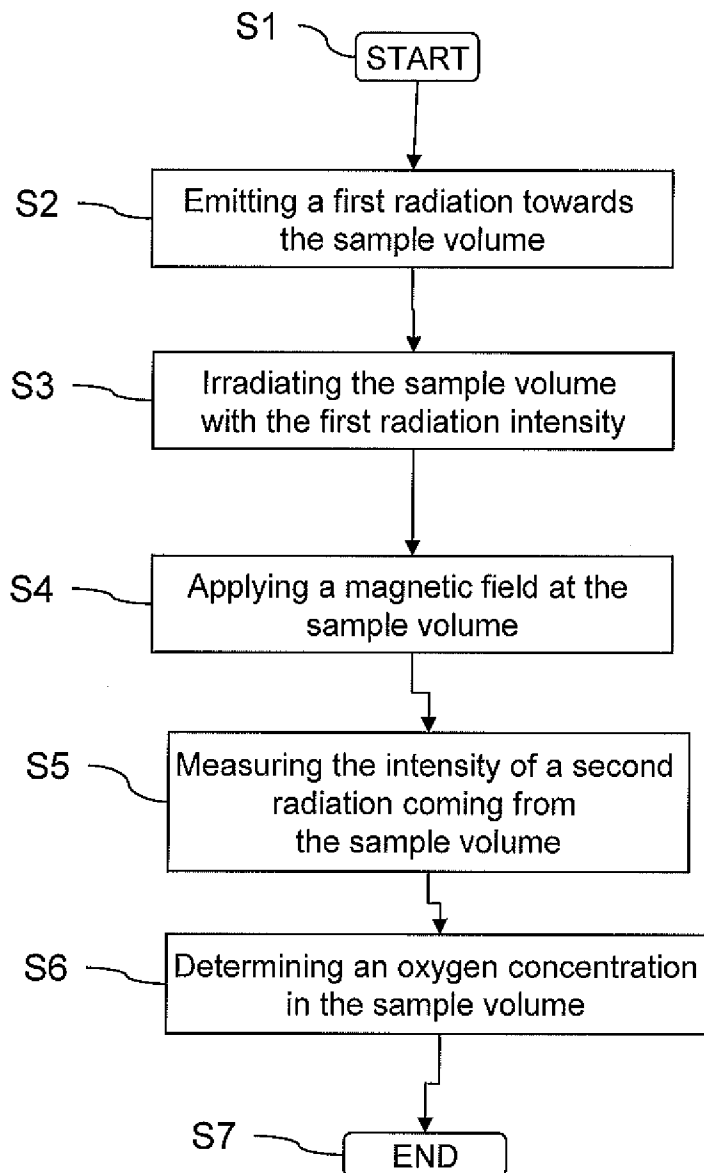


FIG. 4

5/6

**FIG. 5**

6/6

**FIG. 6**

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2009/051941

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N21/31

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N G01J

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

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

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	column 2, lines 3-10, 23-27, 43-51 column 3, line 55 - column 4, line 33 column 4, lines 47-55 column 6, lines 28-42 column 7, lines 12-22 column 8, lines 28-32 figure 2a	16-18
Y	US 4 504 145 A (KOIZUMI HIDEAKI [JP]) 12 March 1985 (1985-03-12) column 1, line 56 - column 2, line 6 column 3, lines 14-38, 51-60 column 4, lines 51-66 column 5, lines 41-45 column 6, lines 6-18	16-18



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

4 September 2009

Date of mailing of the international search report

15/09/2009

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INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2009/051941

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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