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(54) Title: RAPID TEMPERATURE MEASUREMENT BY WAVELENGTH MODULATION SPECTROSCOPY

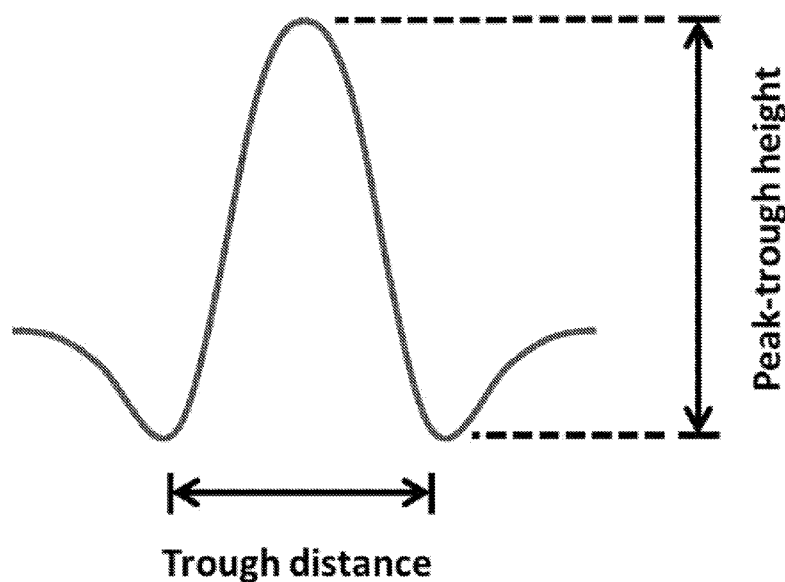


FIG. 1

(57) Abstract: Aspects of the present disclosure describe rapid temperature measurement by wavelength modulation spectroscopy (WMS) that determines gas temperature from  $2f$  signals from two absorption lines by WMS methodologies even when the gas concentration is sufficiently high to saturate optical absorptions. In sharp contrast to the prior art, rapid temperature measurement by WMS according to aspects of the present disclosure employs both a  $2f$  signal ratio and gas concentration determined from the  $2f$  signal.

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## **RAPID TEMPERATURE MEASUREMENT BY WAVELENGTH MODULATION SPECTROSCOPY**

### **CROSS REFERENCE**

**[0001]** This disclosure claims the benefit of United States Provisional Patent Application Serial No. 62/829,668 filed April 5, 2019 and United States Utility Patent Application 16/838,212 filed April 2, 2020 the entire contents of which is incorporated by reference as if set forth at length herein.

### **TECHNICAL FIELD**

**[0002]** This disclosure relates generally to temperature measurement for immediate or later evaluation. More particularly, it describes rapid temperature measurement by wavelength modulation spectroscopy.

### **BACKGROUND**

**[0003]** Wavelength modulation spectroscopy (WMS) is a widely used methodology used to determine trace gas concentrations by measuring a peak (or peak-trough) height of the second harmonic signal ( $2f$ ) of the trace gas' absorption line. Additionally, the peak (or peak-trough) height ratio of  $2f$  signals at two different absorption lines has been used to perform rapid temperature measurement of gases.

**[0004]** However, this temperature measure scheme requires that light absorptions by the gas at the two different lines are sufficiently low such that optical absorption by the gas being measured is not saturated. If the light absorption by the gas at either or both absorption lines is saturated, the peak (or peak-trough) height is nonlinearly dependent on gas concentration. As a result, the  $2f$  signal ratio between the two absorption lines is not a single-value function of temperature and cannot be solely used to determine temperature.

### **SUMMARY**

**[0005]** The above problem is solved and an advance in the art is made according to aspects of the present disclosure directed to a method for determining gas temperature from

$2f$  signals from two absorption lines by WMS methodologies even when the gas concentration is sufficiently high to saturate optical absorptions.

[0006] In sharp contrast to the prior art, rapid temperature measurement by WMS according to aspects of the present disclosure employs both a  $2f$  signal ratio and gas concentration determined from the  $2f$  signal.

#### BRIEF DESCRIPTION OF THE DRAWING

[0007] A more complete understanding of the present disclosure may be realized by reference to the accompanying drawing in which:

[0008] **FIG. 1** shows a schematic plot of an illustrative gas absorption line's  $2f$  signal when gas concentration is low and optical absorption is not saturated according to aspects of the present disclosure;

[0009] **FIG. 2(A)**, **FIG. 2(B)**, and **FIG. 2(C)** are schematic plots illustrating the  $2f$  signal shape evolving as relative gas concentration increases from lowest relative concentration (**FIG. 2(A)**), to medium relative concentration (**FIG. 2(B)**), to highest relative concentration (**FIG. 2(C)**), according to aspects of the present disclosure; and

[0010] **FIG. 3** is a flow diagram illustrating a calibration and WMS quick temperature measurement method according to aspects of the present disclosure; and

[0011] **FIG. 4** is a schematic block diagram illustrating a system and high level process operable for WMS quick temperature measurement method according to aspects of the present disclosure.

[0012] The illustrative embodiments are described more fully by the Figures and detailed description. Embodiments according to this disclosure may, however, be

embodied in various forms and are not limited to specific or illustrative embodiments described in the drawing and detailed description.

## **DESCRIPTION**

**[0013]** The following merely illustrates the principles of the disclosure. It will thus be appreciated that those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the disclosure and are included within its spirit and scope.

**[0014]** Furthermore, all examples and conditional language recited herein are intended to be only for pedagogical purposes to aid the reader in understanding the principles of the disclosure and the concepts contributed by the inventor(s) to furthering the art and are to be construed as being without limitation to such specifically recited examples and conditions.

**[0015]** Moreover, all statements herein reciting principles, aspects, and embodiments of the disclosure, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

**[0016]** Thus, for example, it will be appreciated by those skilled in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the disclosure.

**[0017]** Unless otherwise explicitly specified herein, the FIGs comprising the drawing are not drawn to scale.

**[0018]** By way of some additional background, we begin by noting as is known that molecules can absorb light at certain wavelengths which causes them to transition from a lower energy level to an upper energy level. The amount of light that is absorbed is

proportional to the fraction of molecules in an absorbing quantum state. Laser absorption spectroscopy (LAS) exploits this relationship to provide quantitative measurements of gas temperature and composition/concentration. Wavelength modulation spectroscopy (WMS) is a LAS technique that is known to provide improved measurements of gas(es).

**[0019]** In wavelength modulation spectroscopy (WMS) the wavelength of light emitted from a tunable light source - such as a diode laser - is modulated with a frequency  $f_0$ , while the wavelength is swept over a molecular absorption line of a gas component of interest in a gas sample. As the light propagates along a measurement path through the gas sample, wavelength dependent absorption converts some of the wavelength modulation into an amplitude modulation of the light. Thus, the light will have an overtone spectrum generated by the absorption, the harmonic content of the spectrum being dependent on the width and shape of the molecular absorption line in the gas and the etalons in the optical path of the measuring system. When the light then impinges onto a measuring detector, for example a photodiode, the detector output contains AC components at the modulation frequency  $f_0$  and its higher harmonics  $Mf_0$  ( $M=2,3,4$ , etc.). Demodulating the detector output at one of said higher harmonics - preferably at  $2f$  - shifts the measurement from frequencies near DC, where the light source is noisy, into a higher frequency range, where the noise is lower, thus improving the measurement sensitivity.

**[0020]** Turning now to **FIG. 1**, there it shows a schematic plot of an illustrative gas absorption line's  $2f$  signal when gas concentration is low and optical absorption is not saturated according to aspects of the present disclosure. Also shown in that figure are portions of the plot that define a peak-trough height and trough distance.

**[0021]** **FIG. 2(A)**, **FIG. 2(B)**, and **FIG. 2(C)** are schematic plots illustrating the  $2f$  signal shape evolving/changing as a relative gas concentration increases from a lowest relative concentration (**FIG. 2(A)**), to a medium relative concentration (**FIG. 2(B)**), to a highest relative concentration (**FIG. 2(C)**), according to aspects of the present disclosure.

**[0022]** With simultaneous reference to these figures, it may be observed that in **FIG. 2(A)**, two peaks of a  $2f$  WMS signal for a gas sample exhibit different absorption strengths at two absorption lines at a certain temperature. When the gas concentration increases and the temperature is maintained constant, both peaks become higher due to stronger absorption at both lines – as shown in **FIG. 2(B)**. Note that the ratio of the two peak (or peak-trough) heights, however, stays the same since both peaks grow larger linearly with increasing gas concentration. As such, the same ratio represents (presents) the same temperature in **FIG. 2(A)** as in **FIG. 2(B)**. Note further that if the gas concentration continues to increase, the absorption lines may become saturated, and the peak shape(s) may be distorted and not grow larger linearly with the increasing gas concentration as illustrated by the plot of **FIG. 2(C)**. As may be observed from these figures, while the temperature represented by the plot of **FIG. 2(C)** is the same as that represented by **FIG. 2(A)**, and **FIG. 2(B)**, the height ratio between the two peaks in **FIG. 2(C)** is not the same anymore.

**[0023]** According to aspects of the present disclosure then, a gas concentration is introduced with the peak height ratio to measure the temperature by  $2f$  signal with – according to this inventive disclosure – with saturated absorption peak(s). A calibration method employing a nonlinear fitting curve is utilized to determine / calculate the temperature.

**[0024]** **FIG. 3** is a flow diagram showing a calibration and subsequent quick temperature measurement of  $T$  according to aspects of the present disclosure. With simultaneous reference to that figure and the following, the overall operation proceeds as follows.

**[0025]** Broadly, the gas temperature  $T$  is determined from peak (or peak-trough) height ratio  $R$  and gas concentration  $C$ , according to the following nonlinear function:

$$T = p_1 + p_2 \cdot C \cdot R + p_3 \cdot C^2 \cdot R^2 + p_4 \cdot C^3 \cdot R^3 + p_5 \cdot R + p_6 \cdot C^2 \cdot R^3 + p_7 \cdot C^6 \cdot R^6 + p_8 \cdot C^3 \cdot R^4$$

where  $p_1$  to  $p_8$  are all parameters determined by calibration.

**[0026]** To determine calibration parameters  $p_1$  to  $p_8$ , the following steps are performed:

1. At a known gas temperature  $T$ , measure a current peak (or peak-trough) height ratio  $R$  of two absorption peaks included in the  $2f$  signal for that gas;
2. Determine the current concentration  $C$  from the peak (or peak-trough) height ratio and the trough distance of either one of the peaks;
3. Repeat 1) and 2) at different  $T$ ,  $R$ , or  $C$  for at least 8 times, determining at least 8 groups of  $T$ ,  $R$ , and  $C$ ;
4. Determine  $p_1$  through  $p_8$  by fitting the groups of  $T$ ,  $R$ ,  $C$  by the nonlinear function

$$T = p_1 + p_2 \cdot C \cdot R + p_3 \cdot C^2 \cdot R^2 + p_4 \cdot C^3 \cdot R^3 + p_5 \cdot R + p_6 \cdot C^2 \cdot R^3 + p_7 \cdot C^6 \cdot R^6 + p_8 \cdot C^3 \cdot R^4.$$

**[0027]** With calibration performed one may quickly determine the temperature  $T$  of an unknown gas concentration by:

- 1) Measure the current peak (or peak-trough) height ratio  $R$  of the two absorption peaks in the  $2f$  signal;
- 2) Determine the current concentration  $C$  from the peak (or peak-trough) height and the trough distance of either one of the two absorption peaks of in the  $2f$  signal;
- 3) To determine  $T$ , substitute the measured values of  $R$  and  $C$  into the nonlinear equation

$$T = p_1 + p_2 \cdot C \cdot R + p_3 \cdot C^2 \cdot R^2 + p_4 \cdot C^3 \cdot R^3 + p_5 \cdot R + p_6 \cdot C^2 \cdot R^3 + p_7 \cdot C^6 \cdot R^6 + p_8 \cdot C^3 \cdot R^4.$$

**[0028]** Operationally, such calibration and temperature measurement may be advantageously performed by a system such as that shown in **FIG. 4** in conjunction with a digital computer to perform the computational determinations. Such computational apparatus – in conjunction with the WMS apparatus shown in the figure – may be employed to construct a quick temperature measuring WMS apparatus that when programmed to perform our inventive method steps.

**[0029]** While we have presented this disclosure using some specific examples, those skilled in the art will recognize that our teachings are not so limited. Accordingly, this disclosure should be only limited by the scope of the claims attached hereto.

## Claims:

1. A wavelength modulation spectroscopy (WMS) method for rapid temperature measurement of a gas comprising:

determining the gas temperature  $T$  from a peak or peak-trough height ratio  $R$  obtained from a WMS  $2f$  signal and gas concentration  $C$ , according to the following nonlinear function

$$T = p_1 + p_2 \cdot C \cdot R + p_3 \cdot C^2 \cdot R^2 + p_4 \cdot C^3 \cdot R^3 + p_5 \cdot R + p_6 \cdot C^2 \cdot R^3 + p_7 \cdot C^6 \cdot R^6 + p_8 \cdot C^3 \cdot R^4$$

where  $p_1$  to  $p_8$  are all parameters determined by calibration.

2. The wavelength modulation spectroscopy method for rapid temperature measurement of a gas according to claim 1 further comprising:

determining a set of calibration parameters  $p_1$  to  $p_8$  by

- i) At a known gas temperature  $T$ , measure a peak or peak-trough height ratio  $R$  of two absorption peaks included in the  $2f$  signal for that gas;
- ii) Determine the current concentration  $C$  from the peak (or peak-trough) height ratio and the trough distance of either one of the peaks;
- iii) Repeat i) and ii) at different  $T$ ,  $R$ , or  $C$  for at least 8 times, determining at least 8 groups of  $T$ ,  $R$ , and  $C$ ; and

determining  $p_1$  through  $p_8$  by fitting the groups of  $T$ ,  $R$ ,  $C$  by the nonlinear function

$$T = p_1 + p_2 \cdot C \cdot R + p_3 \cdot C^2 \cdot R^2 + p_4 \cdot C^3 \cdot R^3 + p_5 \cdot R + p_6 \cdot C^2 \cdot R^3 + p_7 \cdot C^6 \cdot R^6 + p_8 \cdot C^3 \cdot R^4.$$

3. The wavelength modulation method for rapid temperature measurement of a gas according to claim 2 further comprising:

measure the peak or peak-trough height ratio  $R$  of two absorption peaks in the  $2f$  signal;

determine the current concentration  $C$  from the peak or peak-trough height and trough distance of either one of the two absorption peaks in the  $2f$  signal;

determine  $T$ , by substituting the measured values of  $R$  and  $C$  into the nonlinear equation

$$T = p_1 + p_2 \cdot C \cdot R + p_3 \cdot C^2 \cdot R^2 + p_4 \cdot C^3 \cdot R^3 + p_5 \cdot R + p_6 \cdot C^2 \cdot R^3 + p_7 \cdot C^6 \cdot R^6 + p_8 \cdot C^3 \cdot R^4.$$

4. The wavelength modulation method for rapid temperature measurement of a gas according to claim 3 wherein the gas is of unknown concentration.

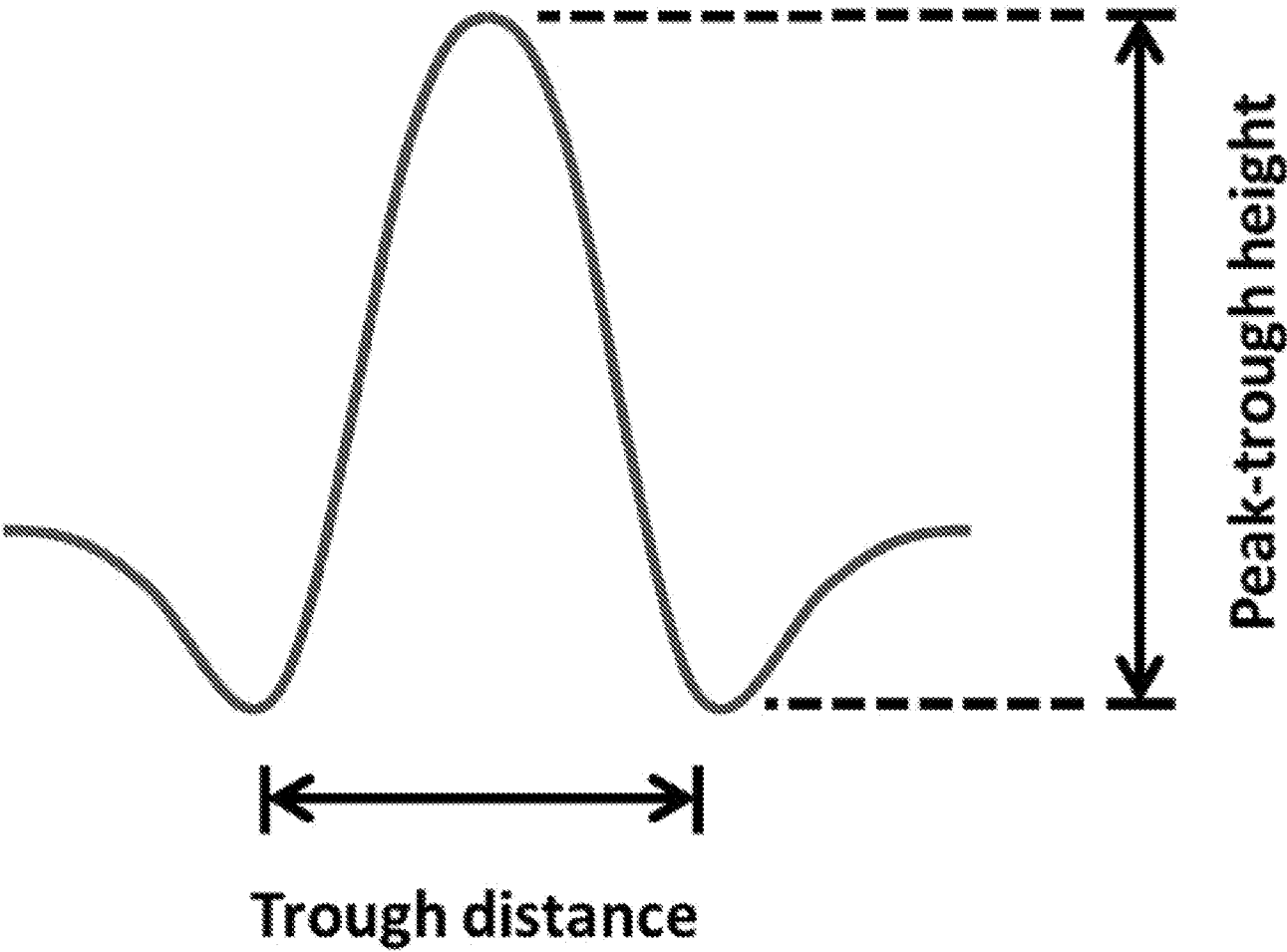


*FIG. 1*

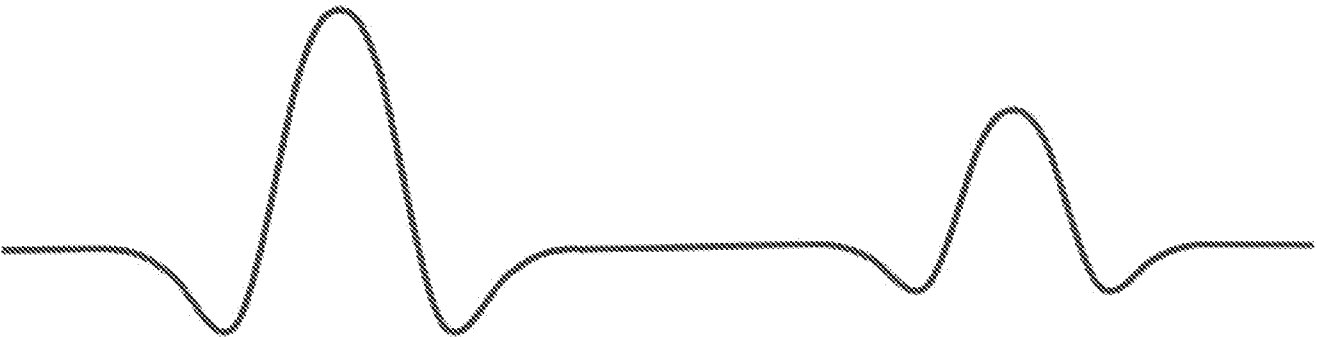


***FIG. 2(A)***

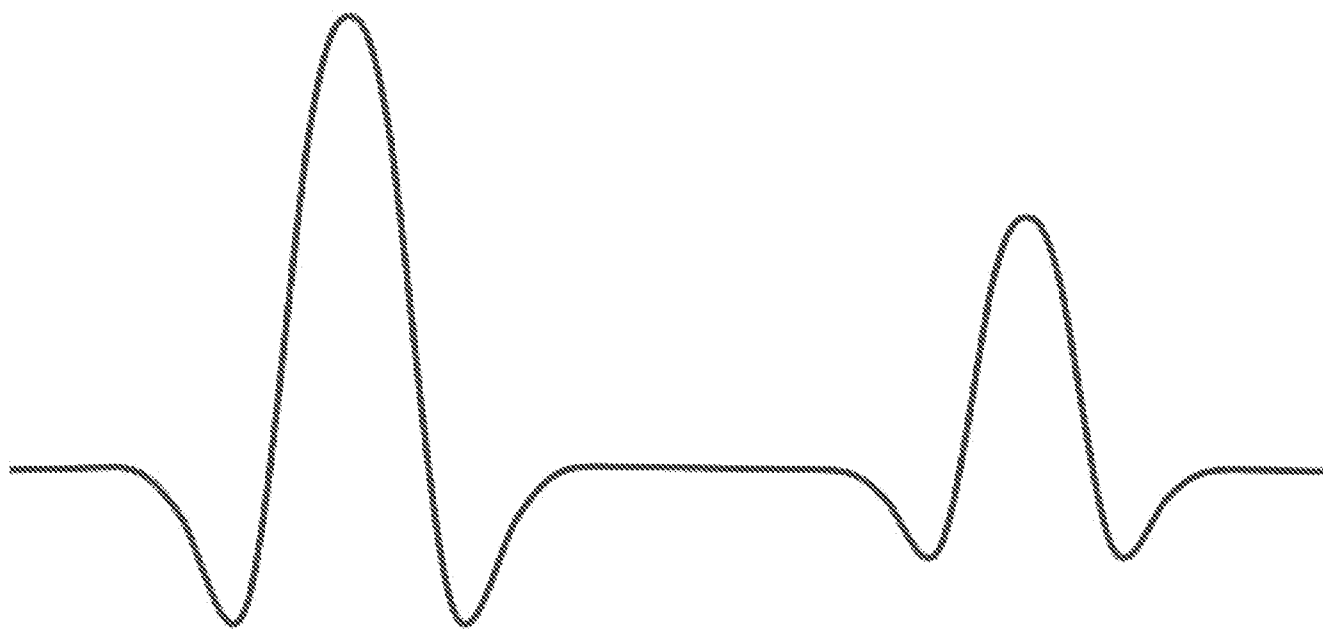


***FIG. 2(B)***

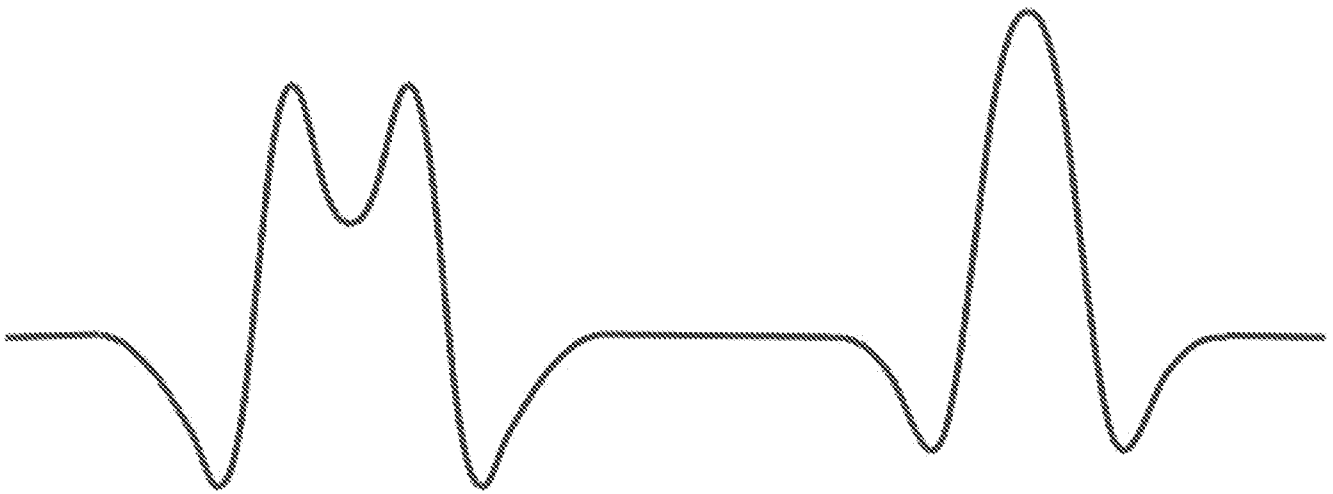
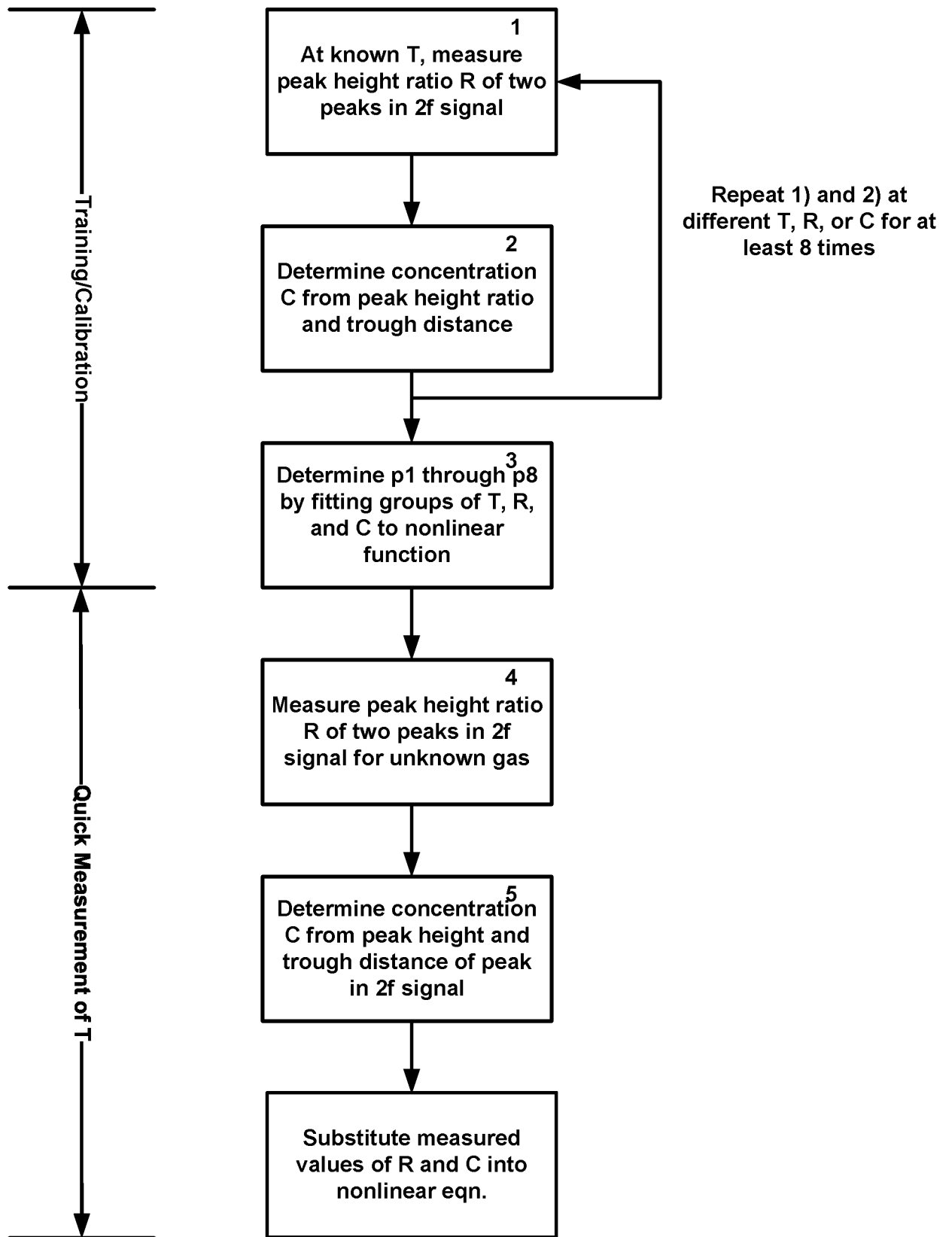
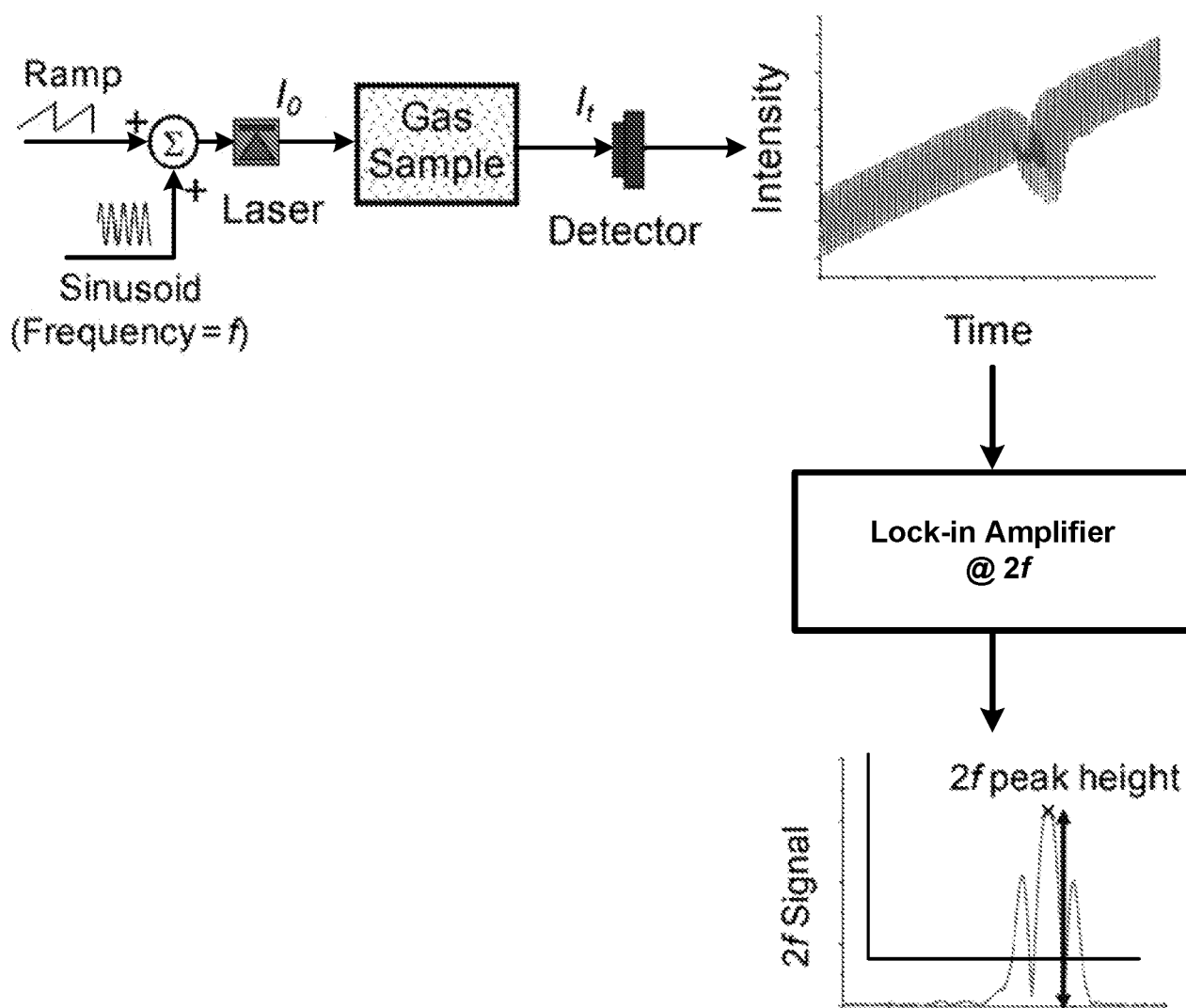


***FIG. 2(C)***

**FIG. 3**

**FIG. 4**

**A. CLASSIFICATION OF SUBJECT MATTER****G01J 3/433(2006.01)i, G01N 21/39(2006.01)i, G01N 21/27(2006.01)i, G01J 3/28(2006.01)i**

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)

G01J 3/433; G01J 3/42; G01K 11/12; G01N 15/02; G01N 21/59; G01N 21/61; G01N 21/39; G01N 21/27; G01J 3/28

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) &amp; Keywords:WMS, trace gas, temperature, 2f signal, nonlinear function

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                        | Relevant to claim No. |
|-----------|---------------------------------------------------------------------------------------------------------------------------|-----------------------|
| A         | US 2011-0150035 A1 (RONALD K. HANSON et al.) 23 June 2011<br>See paragraph [0095], claim 1 and figures 1-16.              | 1-4                   |
| A         | WO 2018-223107 A1 (NEC LABORATORIES AMERICA, INC.) 06 December 2018<br>See paragraph [0042], claims 1-12 and figures 1-5. | 1-4                   |
| A         | WO 2010-042300 A1 (GE INFRASTRUCTURE SENSING, INC. et al.) 15 April 2010<br>See claim 1.                                  | 1-4                   |
| A         | US 2014-0049777 A1 (KANG SUN et al.) 20 February 2014<br>See paragraphs [0024]-[0060] and figures 1-9.                    | 1-4                   |
| A         | US 2012-0283961 A1 (ANDREAS WITTMANN et al.) 08 November 2012<br>See claims 1-10.                                         | 1-4                   |



Further documents are listed in the continuation of Box C.



See patent family annex.

\* Special categories of cited documents:

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"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

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Date of mailing of the international search report

**28 July 2020 (28.07.2020)**

Name and mailing address of the ISA/KR

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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/US2020/026504**

| Patent document<br>cited in search report | Publication<br>date | Patent family<br>member(s)                                                                                                                                                                                                                                                                | Publication<br>date                                                                                                                                                                                            |
|-------------------------------------------|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| US 2011-0150035 A1                        | 23/06/2011          | None                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                |
| WO 2018-223107 A1                         | 06/12/2018          | US 10670517 B2<br>US 2019-0170638 A1                                                                                                                                                                                                                                                      | 02/06/2020<br>06/06/2019                                                                                                                                                                                       |
| WO 2010-042300 A1                         | 15/04/2010          | BR PI0914076 A2<br>CN 102177422 A<br>CN 102177422 B<br>EP 2338042 A1<br>JP 2012-505404 A<br>JP 5603870 B2<br>KR 10-1425167 B1<br>US 2009-0173965 A1<br>US 2010-0089117 A1<br>US 2011-0181876 A1<br>US 2011-0181877 A1<br>US 7781248 B2<br>US 7943915 B2<br>US 8026499 B2<br>US 8217376 B2 | 29/05/2018<br>07/09/2011<br>09/07/2014<br>29/06/2011<br>01/03/2012<br>08/10/2014<br>31/07/2014<br>09/07/2009<br>15/04/2010<br>28/07/2011<br>28/07/2011<br>24/08/2010<br>17/05/2011<br>27/09/2011<br>10/07/2012 |
| US 2014-0049777 A1                        | 20/02/2014          | US 8970842 B2                                                                                                                                                                                                                                                                             | 03/03/2015                                                                                                                                                                                                     |
| US 2012-0283961 A1                        | 08/11/2012          | CN 102768197 A<br>CN 102768197 B<br>EP 2520925 A1<br>EP 2520925 B1<br>JP 2012-233900 A<br>JP 5528497 B2<br>US 9140644 B2                                                                                                                                                                  | 07/11/2012<br>06/06/2017<br>07/11/2012<br>01/05/2013<br>29/11/2012<br>25/06/2014<br>22/09/2015                                                                                                                 |