US 20250258092A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2025/0258092 A1**

Wilkes et al. (43) **Pub. Date: Aug. 14, 2025**

(54) **MULTI-GAS SENSING AND DETECTION SYSTEM**

(71) Applicant: **Heath Consultants Incorporated**, Houston, TX (US)

(72) Inventors: **John Wilkes**, Cambridgeshire (GB); **Euan Smith**, Cambridgeshire (GB); **Duncan Wales**, Cambridgeshire (GB); **Matthew Homburg**, Cambridgeshire (GB); **Joe Griffiths**, Cambridgeshire (GB); **Vineet Aggarwal**, Richmond, TX (US)

(73) Assignee: **Heath Consultants Incorporated**, Houston, TX (US)

(21) Appl. No.: **19/053,210**

(22) Filed: **Feb. 13, 2025**

Related U.S. Application Data

(60) Provisional application No. 63/552,978, filed on Feb. 13, 2024, provisional application No. 63/552,996, filed on Feb. 13, 2024.

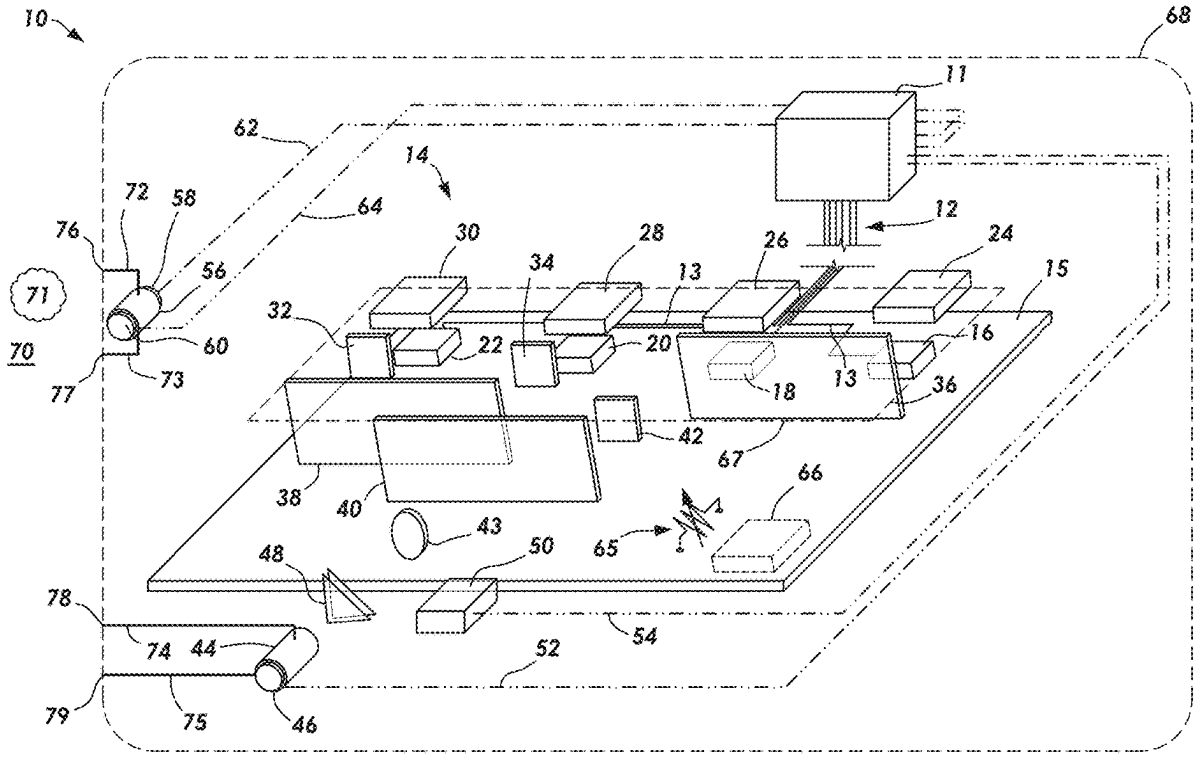
Publication Classification

(51) **Int. Cl.**
G01N 21/3504 (2014.01)

(52) **U.S. Cl.**
CPC . ***G01N 21/3504*** (2013.01); *G01N 2201/0633* (2013.01); *G01N 2201/068* (2013.01)

(57) **ABSTRACT**

A non-dispersive near infrared light is used for detecting analyte gases in a testing zone. A sample obtained from the testing zone is irradiated with a reference light and with test lights. The test lights are emitted in sequence and modulated to be out of phase with the reference light. Frequencies of the test lights are in the absorption bands of particular analyte gases, with the reference light frequency being outside of the absorption bands. Analyte presence in the sample is identified by sensing changes in differences over time of test light and reference light intensity. Before irradiating the sample, the lights are optically conditioned by aligning them on the same path, and splitting the bandwidth of some lights for detecting analytes with overlapping absorption bands.



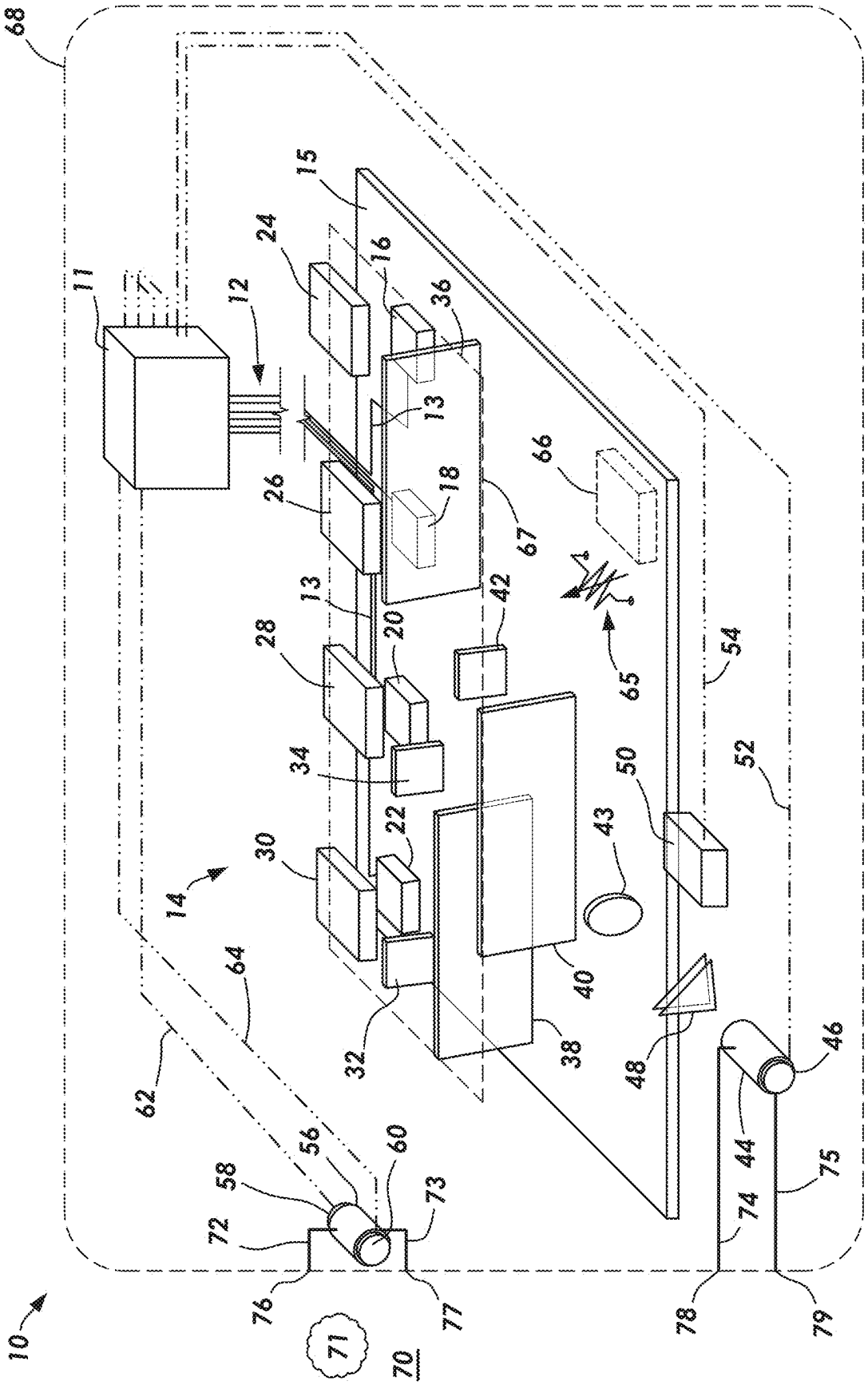

68
15
24
16
36
11
12
13
66
26
18
67
13
42
28
20
65
54
34
50
52
22
43
30
14
64
40
32
38
48
46
62
56
60
58
73
44
75
72
74
76
77
78
79
71
70
10

FIG. 1

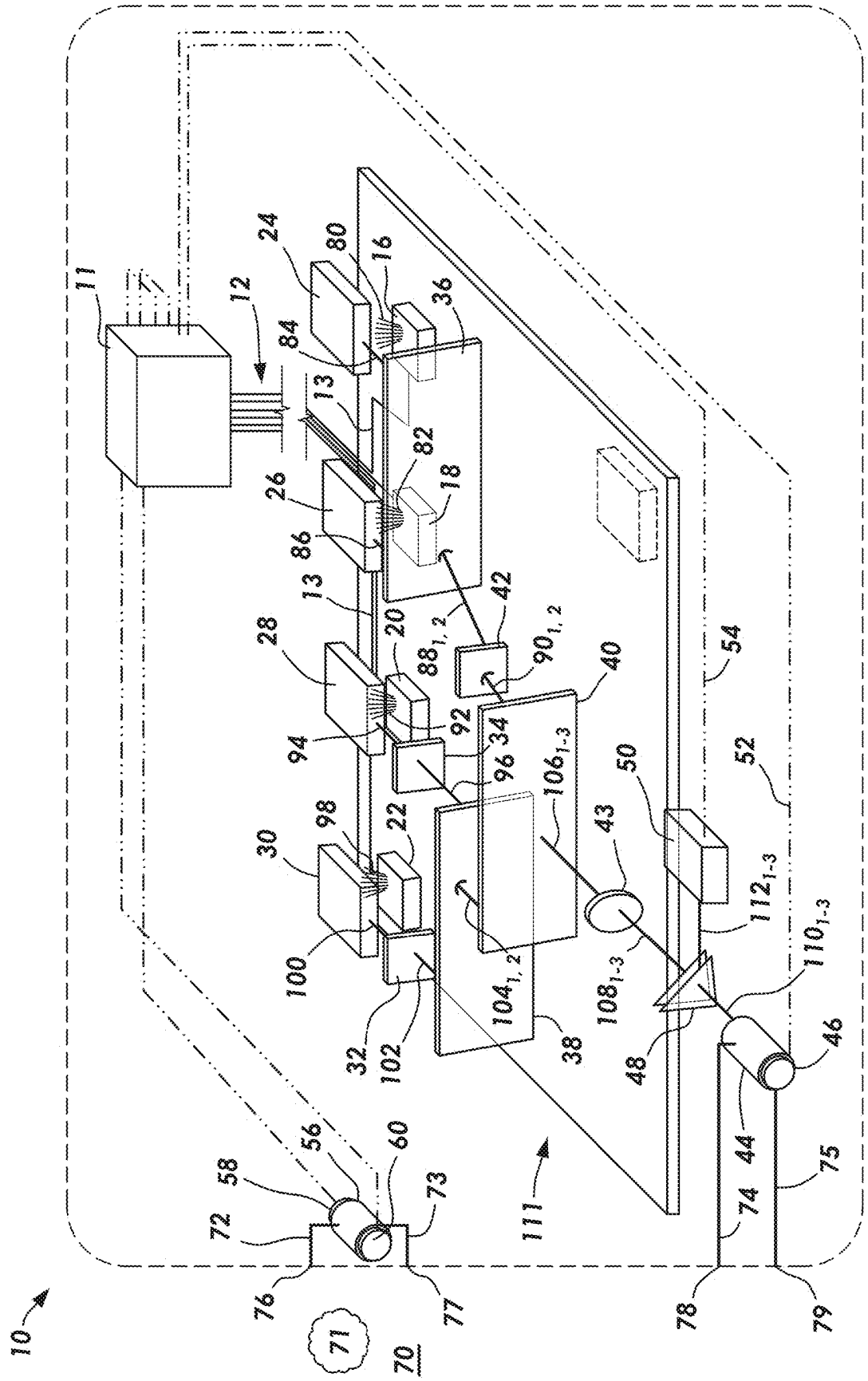

10
11
12
13
16
18
20
22
24
26
28
30
32
34
36
38
40
42
43
44
46
48
50
52
54
56
58
60
70
71
72
73
74
75
76
77
78
79
80
82
84
86
88 1, 2
90 1, 2
92
94
96
98
100
102
104 1, 2
106 1-3
108 1-3
110 1-3
111
112 1-3

FIG. 2

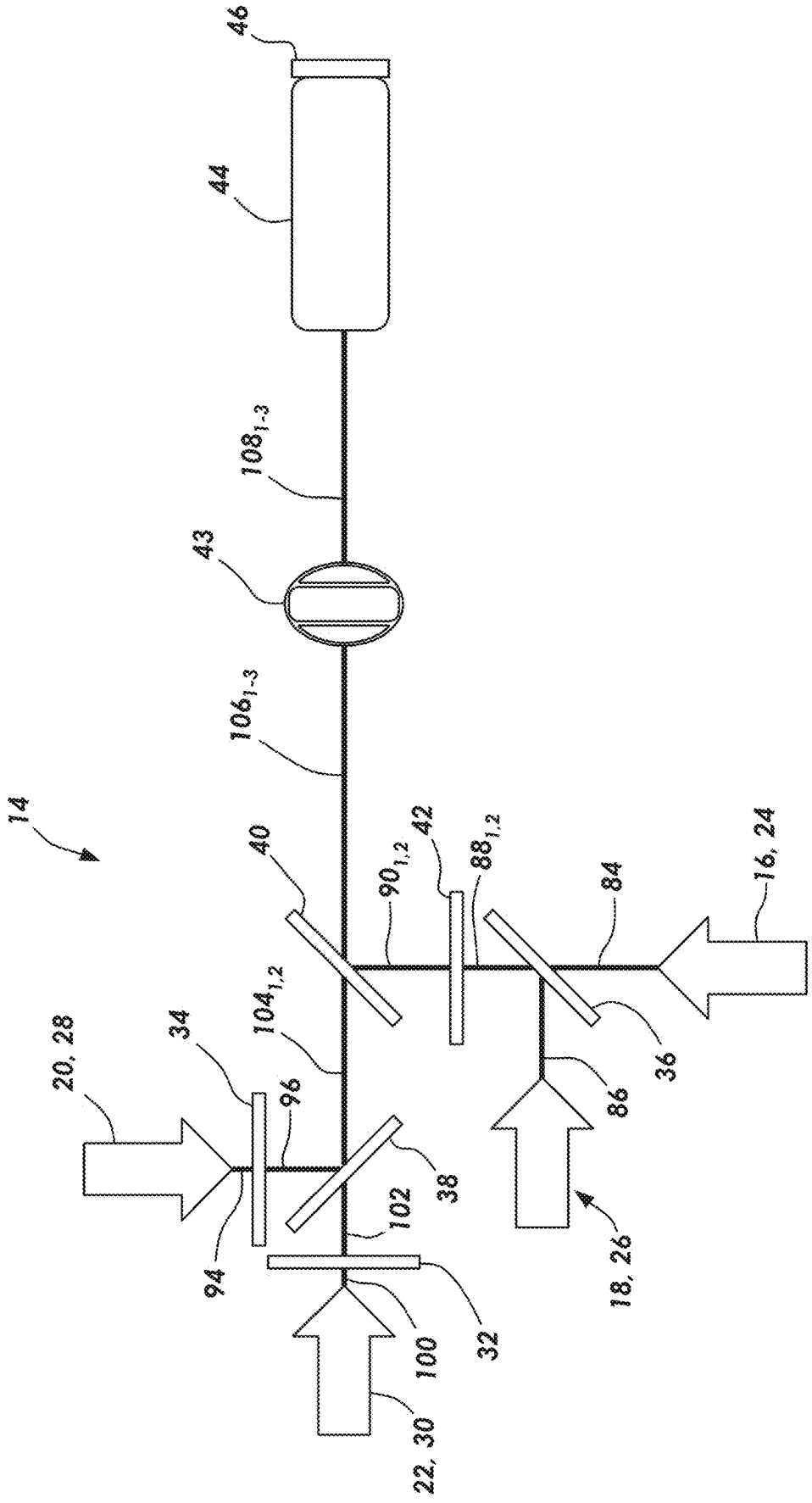

46
44
108_{1-3}
43
106_{1-3}
14
40
$90_{1,2}$
42
$88_{1,2}$
84
16, 24
$104_{1,2}$
20, 28
34
96
36
86
38
102
94
18, 26
32
100
22, 30

FIG. 2A

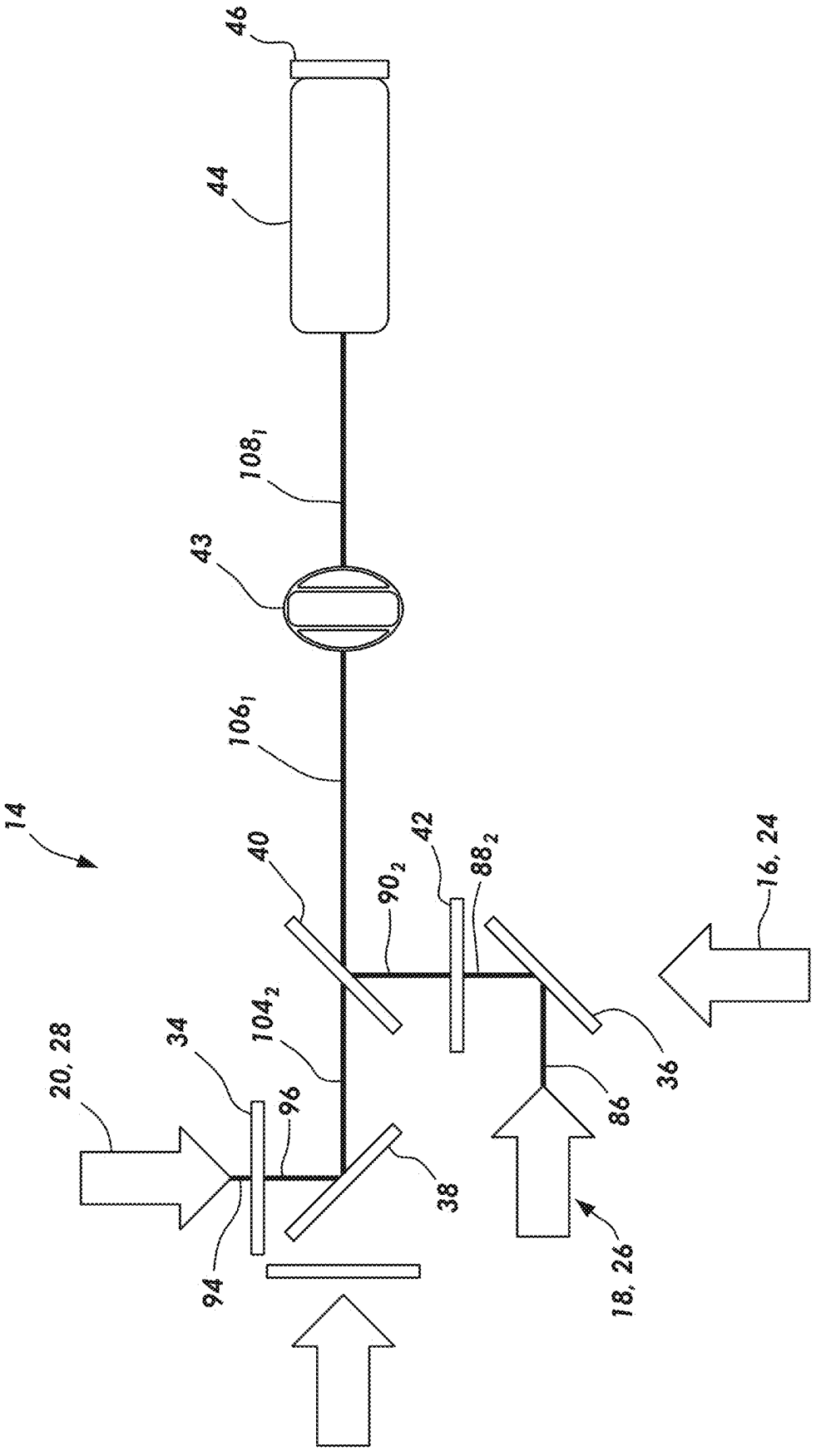

46
44
108_1
43
106_1
14
40
90_2
42
88_2
16, 24
104_2
34
20, 28
96
36
86
38
94
18, 26

FIG. 2B

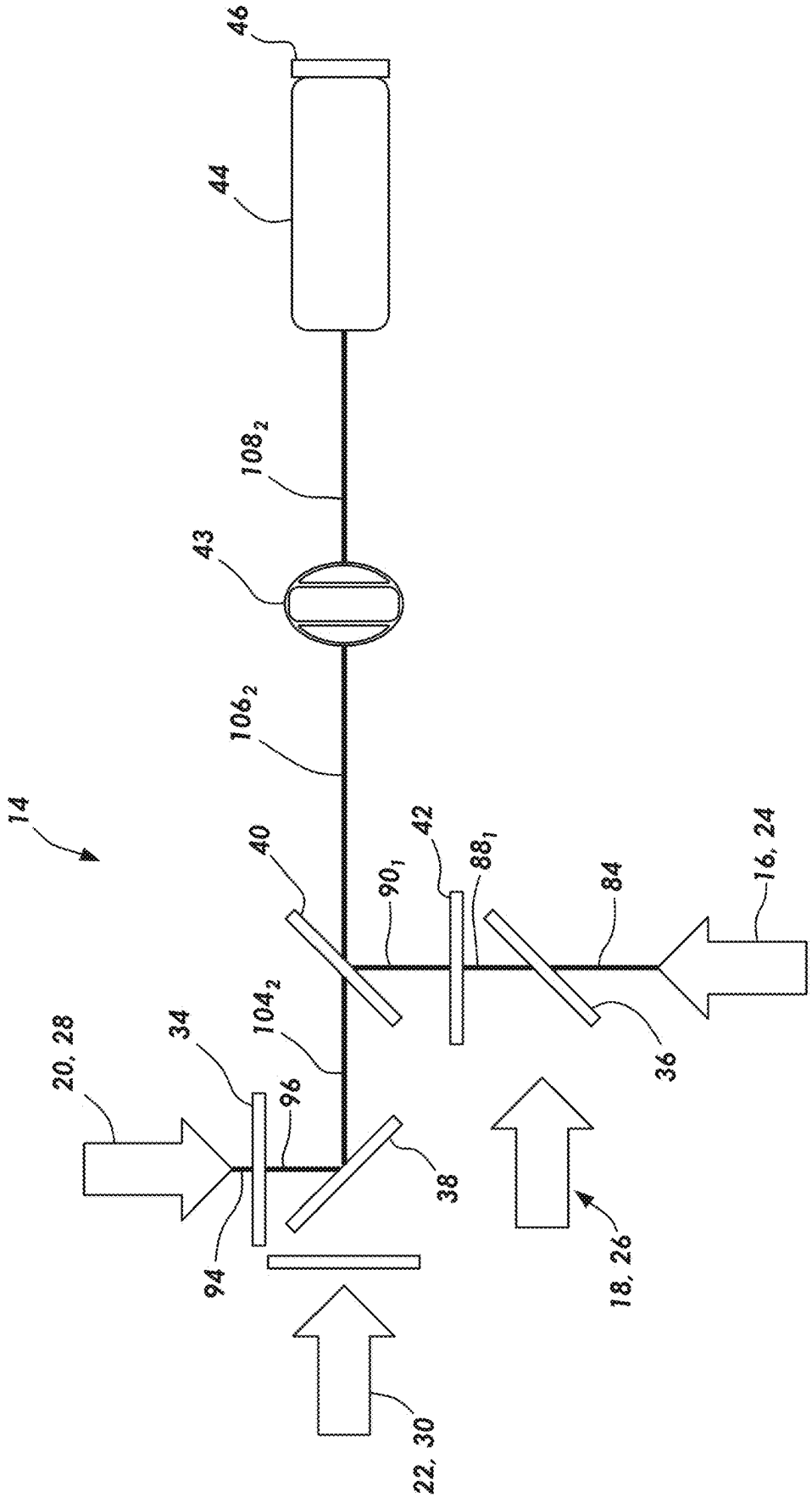

46
44
108_2
43
106_2
14
40
90_1
42
88_1
84
16, 24
104_2
34
20, 28
96
38
36
94
18, 26
22, 30

FIG. 2C

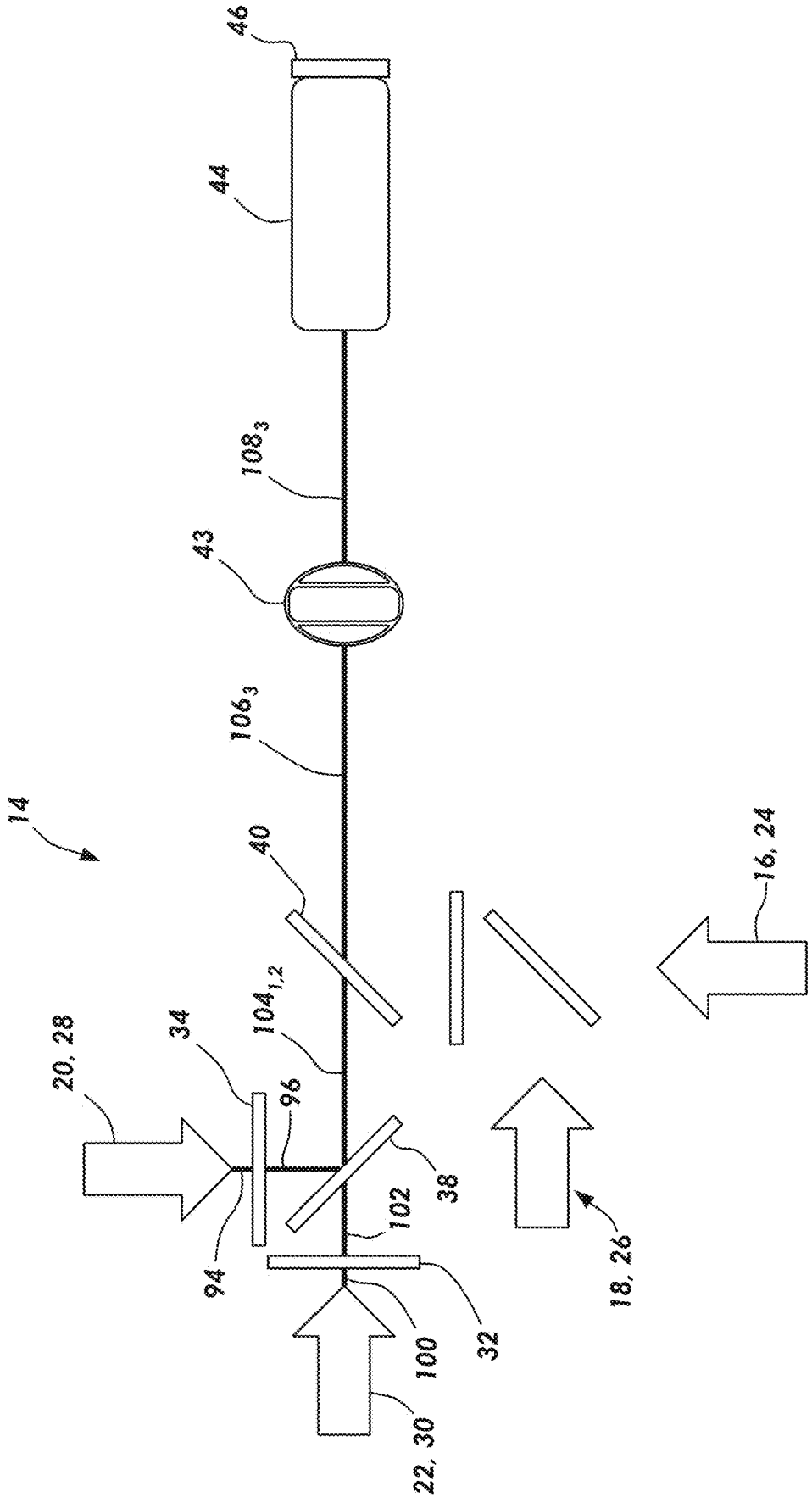

46
44
108_3
43
106_3
14
40
$104_{1,2}$
34
20, 28
96
94
102
38
100
32
22, 30
18, 26
16, 24

FIG. 2D

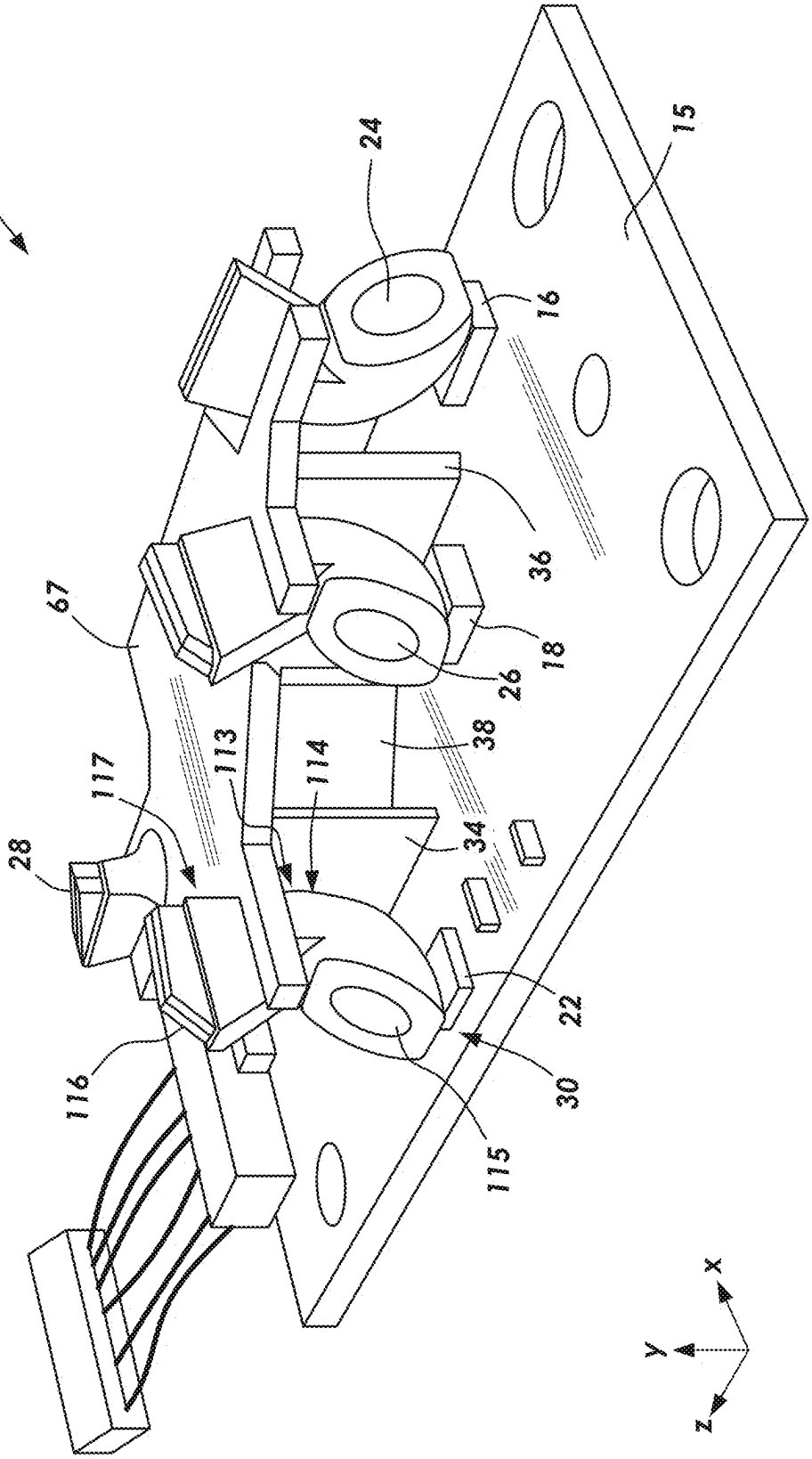


FIG. 2E

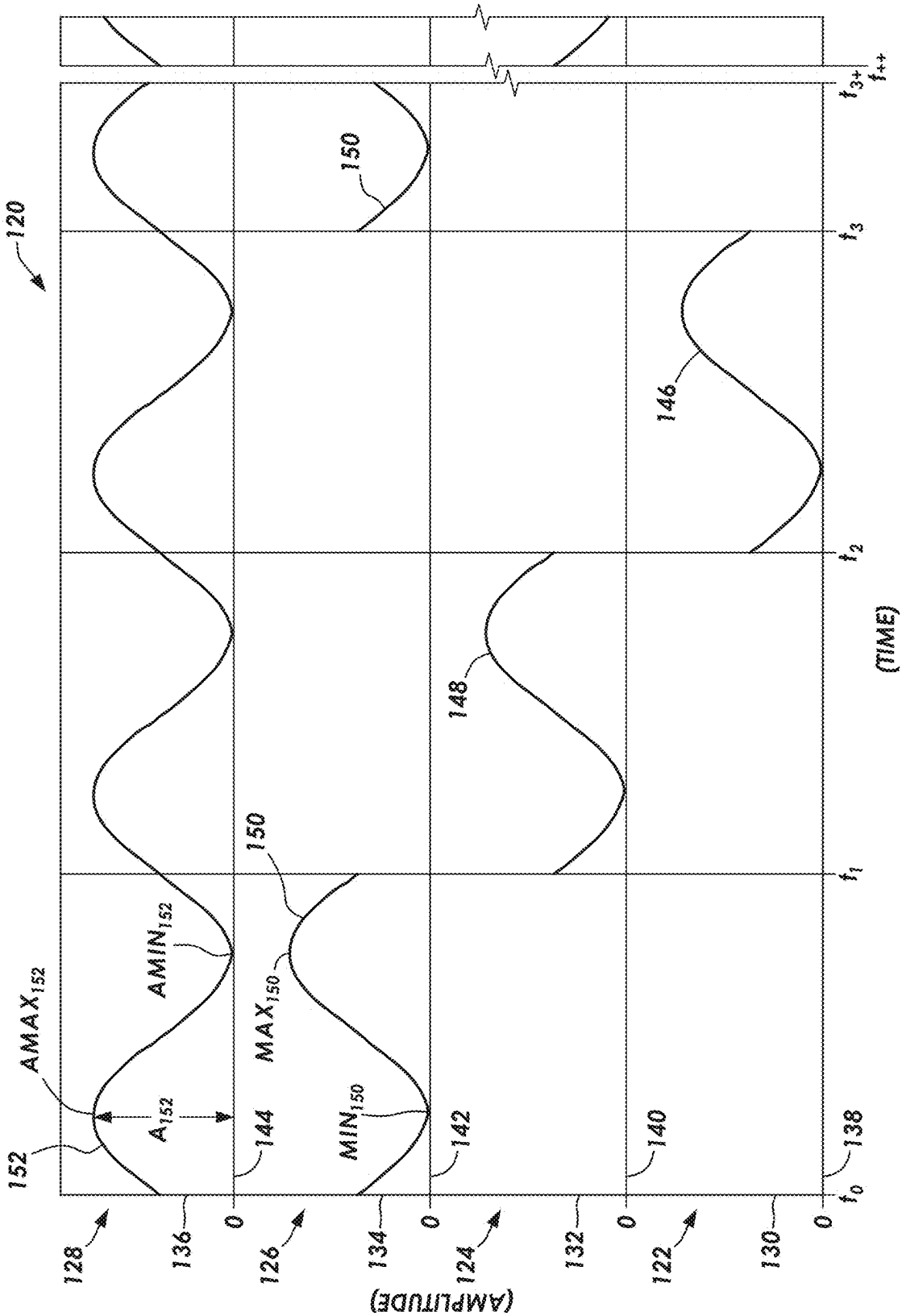

120
152
AMAX152
AMIN152
A152
MAX150
MIN150
150
144
142
140
138
148
146
128
136
126
134
124
132
122
130
0
t0
t1
t2
t3
t3+
t++
(TIME)
(AMPLITUDE)

FIG. 3A

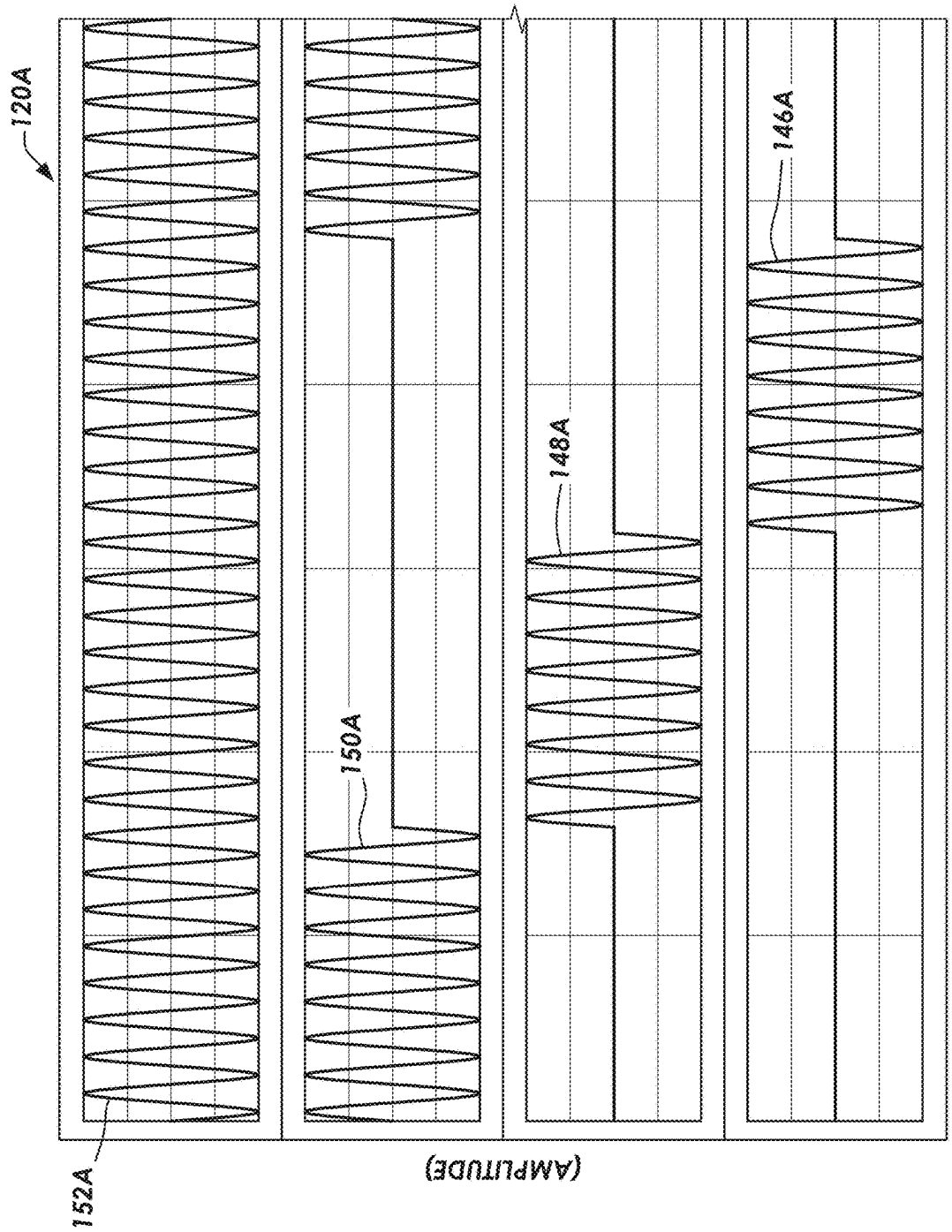


FIG. 3B

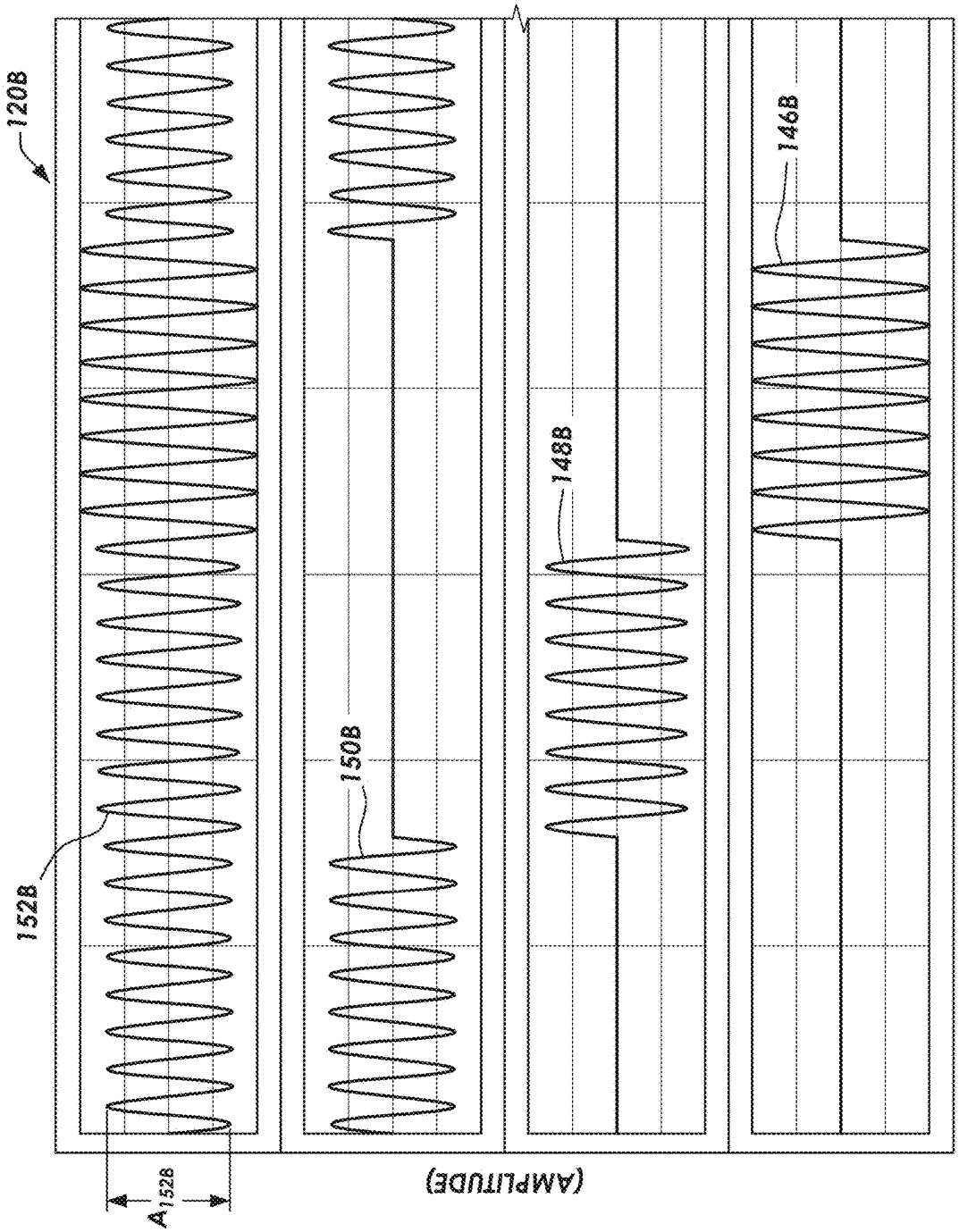


FIG. 3C

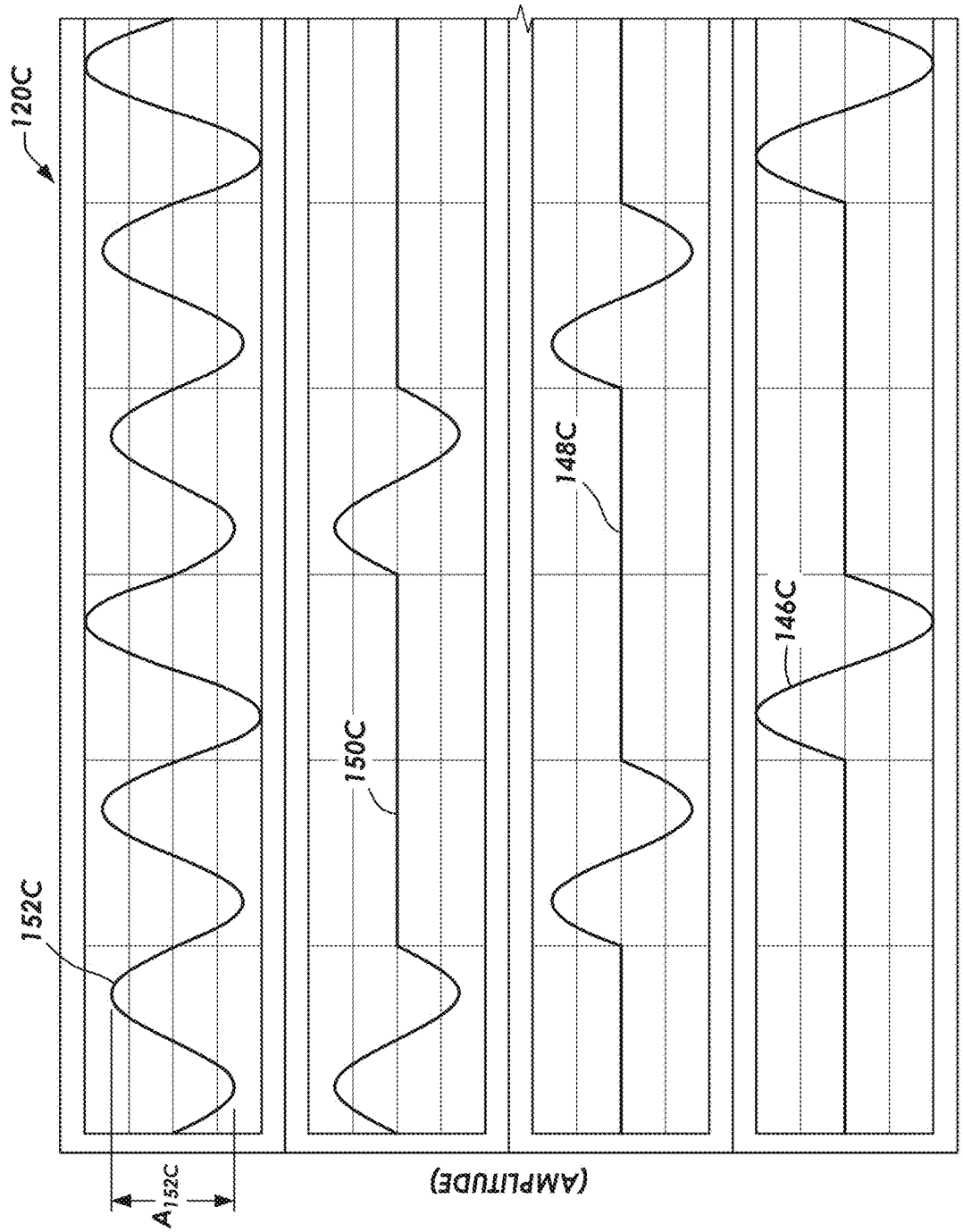


FIG. 3D

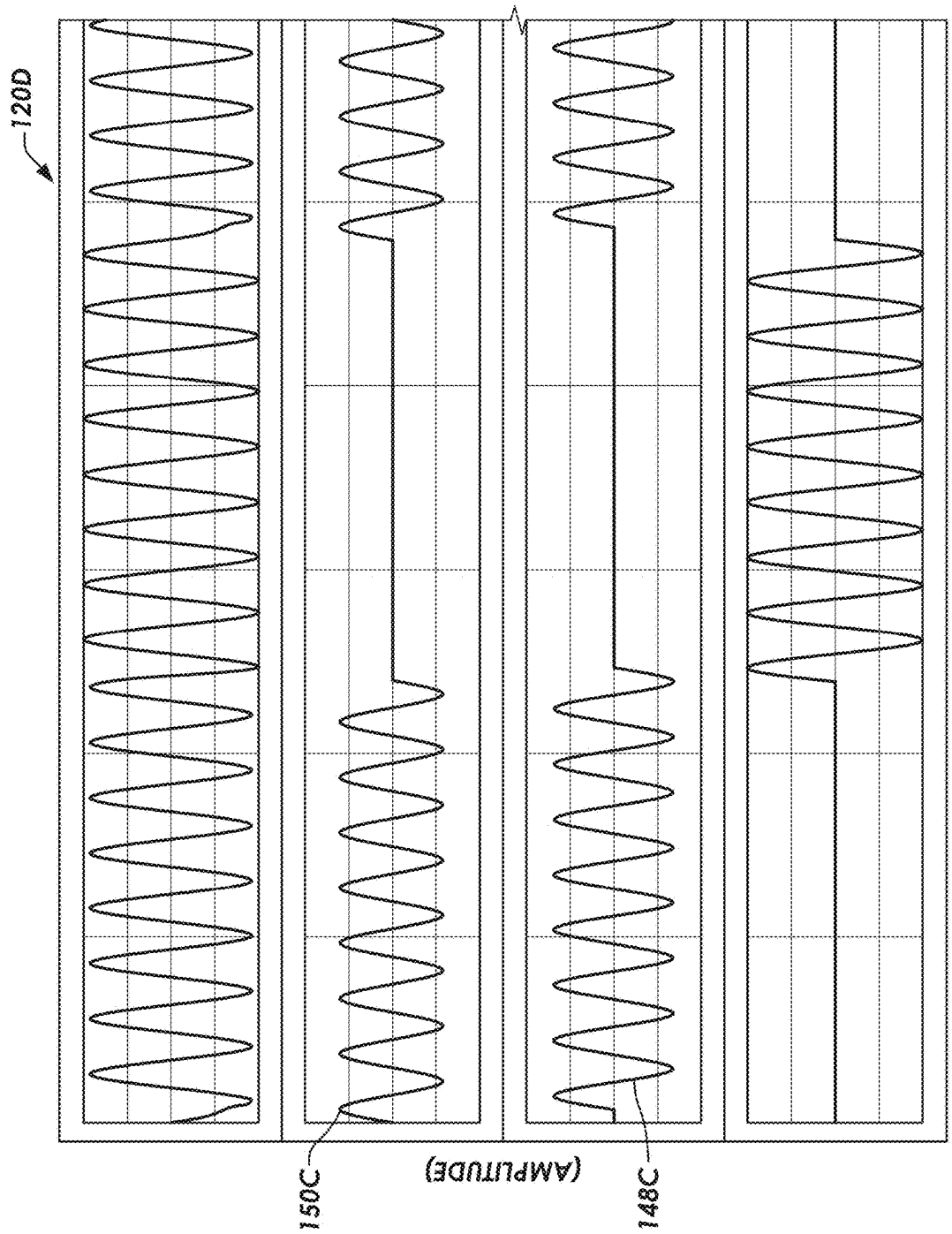


FIG. 3E

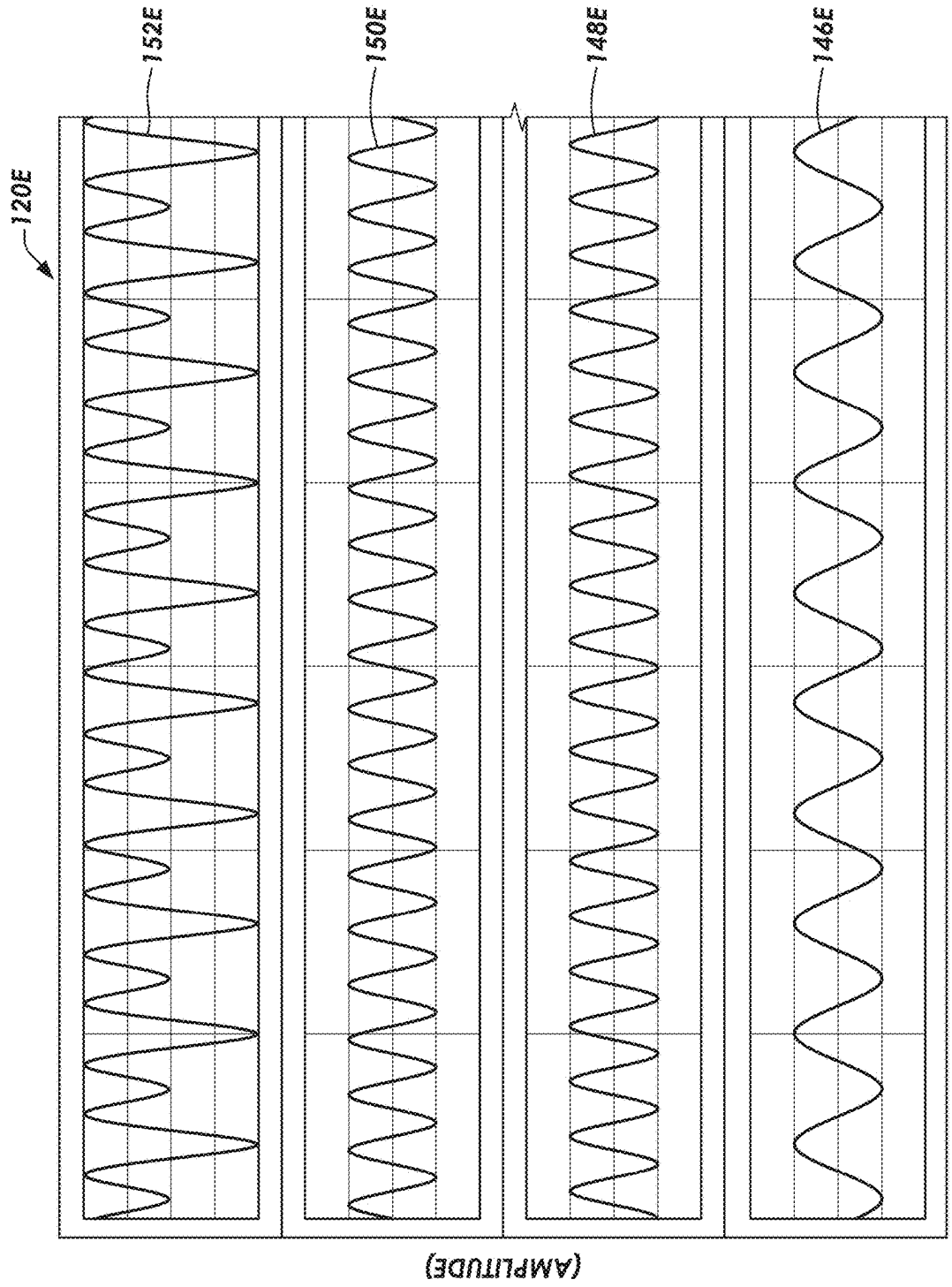


FIG. 3F

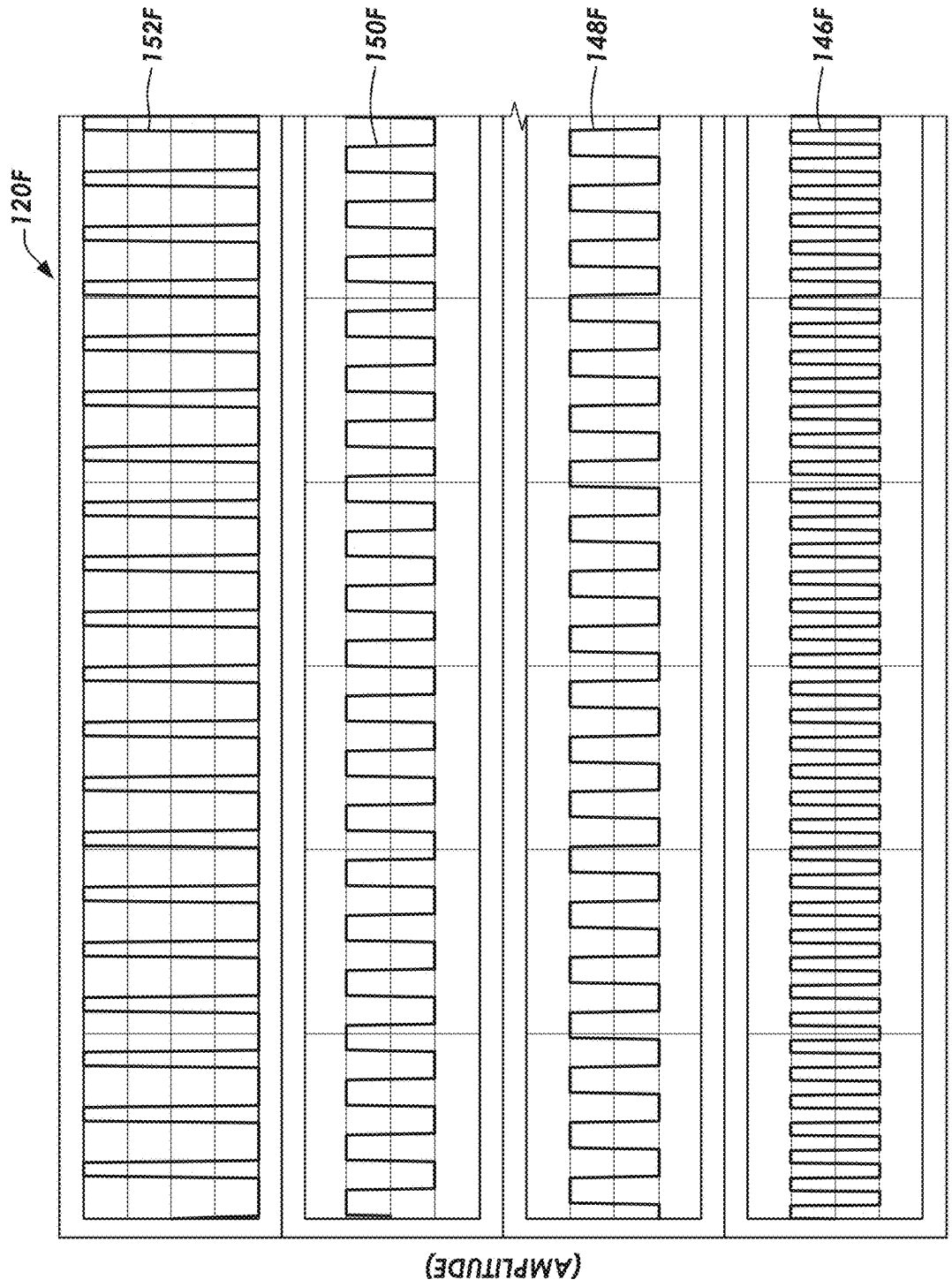


FIG. 3G

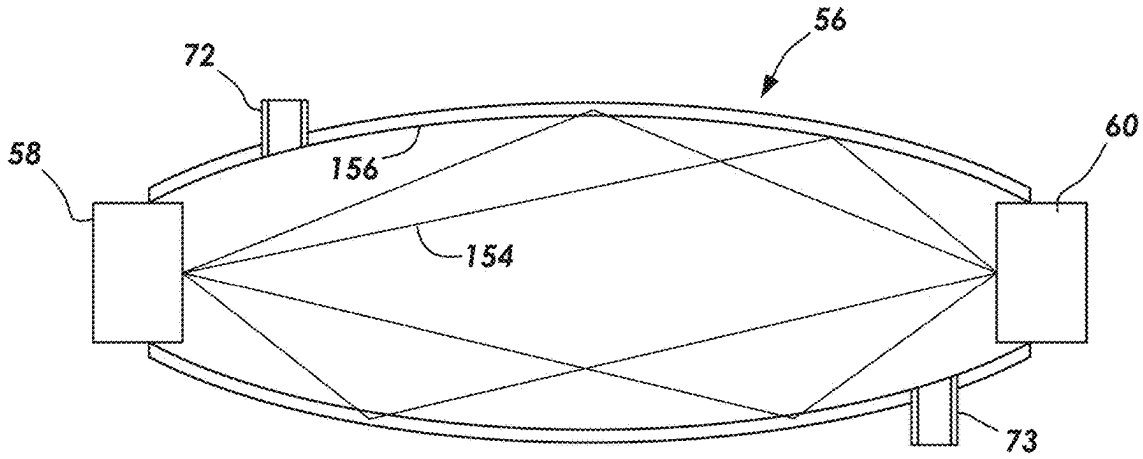

56
72
58
156
60
154
73

FIG. 4

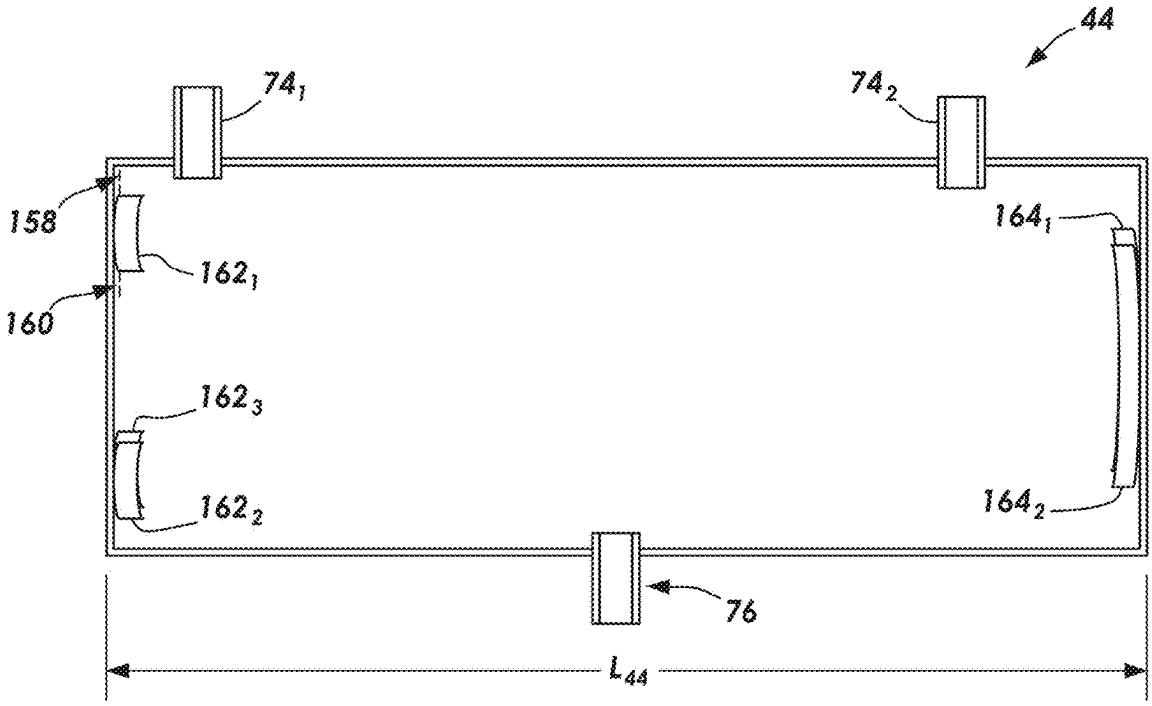

44
74₁
74₂
158
164₁
162₁
160
162₃
162₂
164₂
76
L₄₄

FIG. 5

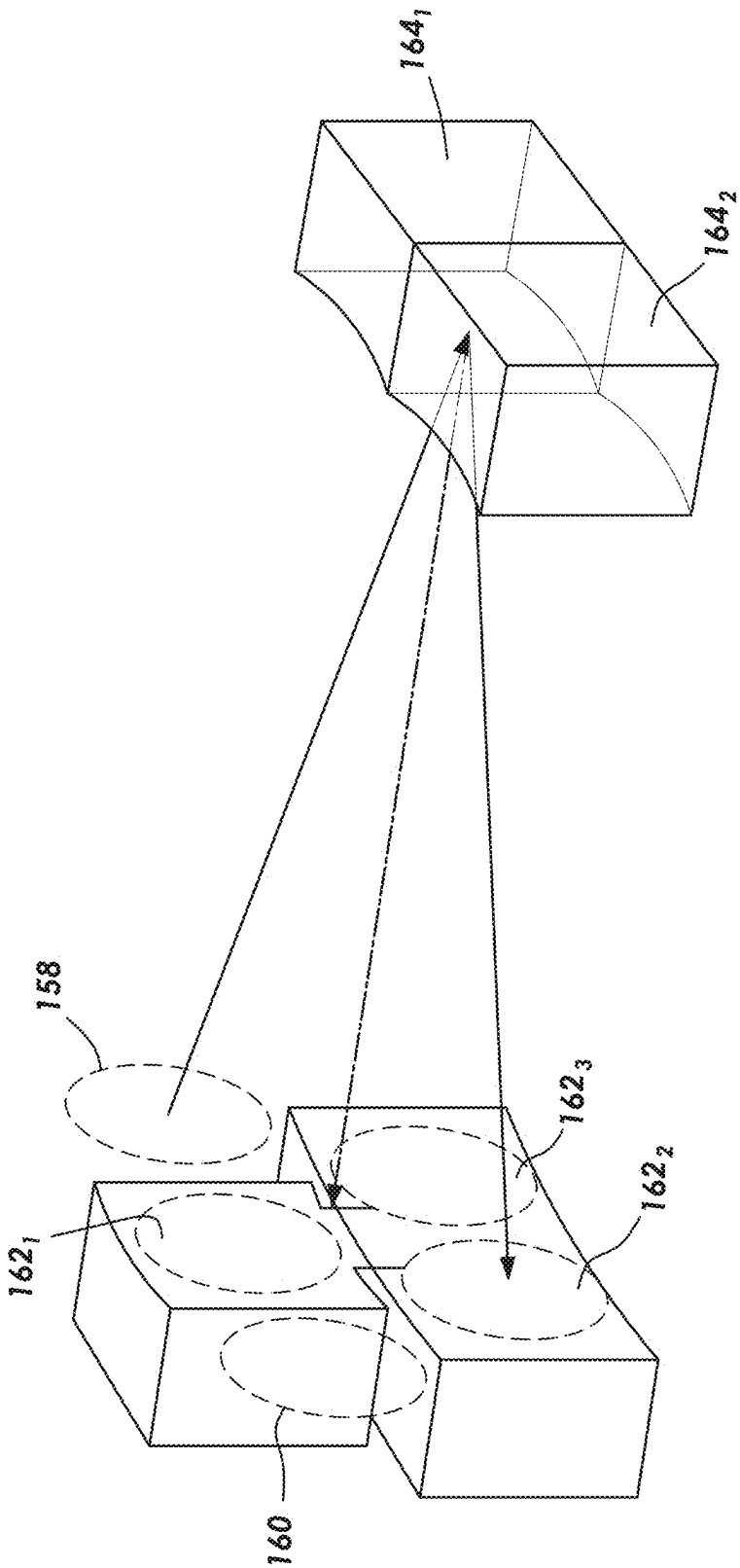


FIG. 5A

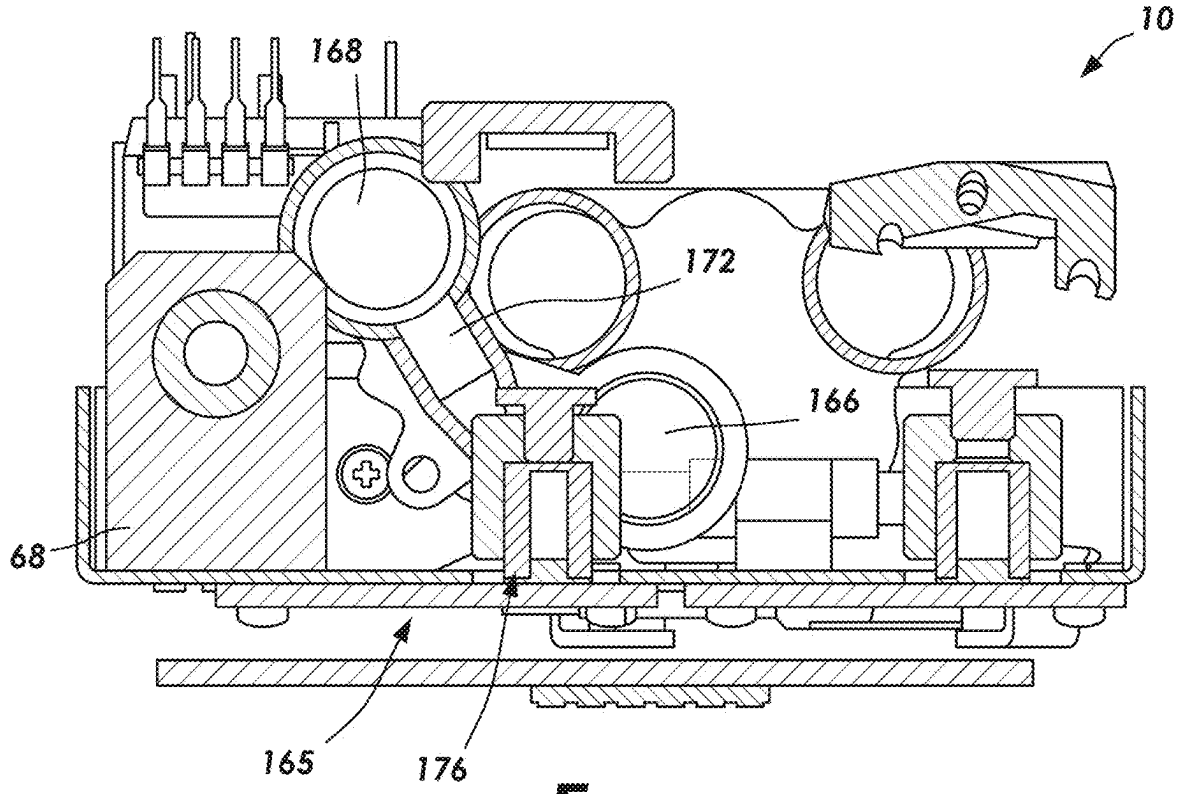


FIG. 6A

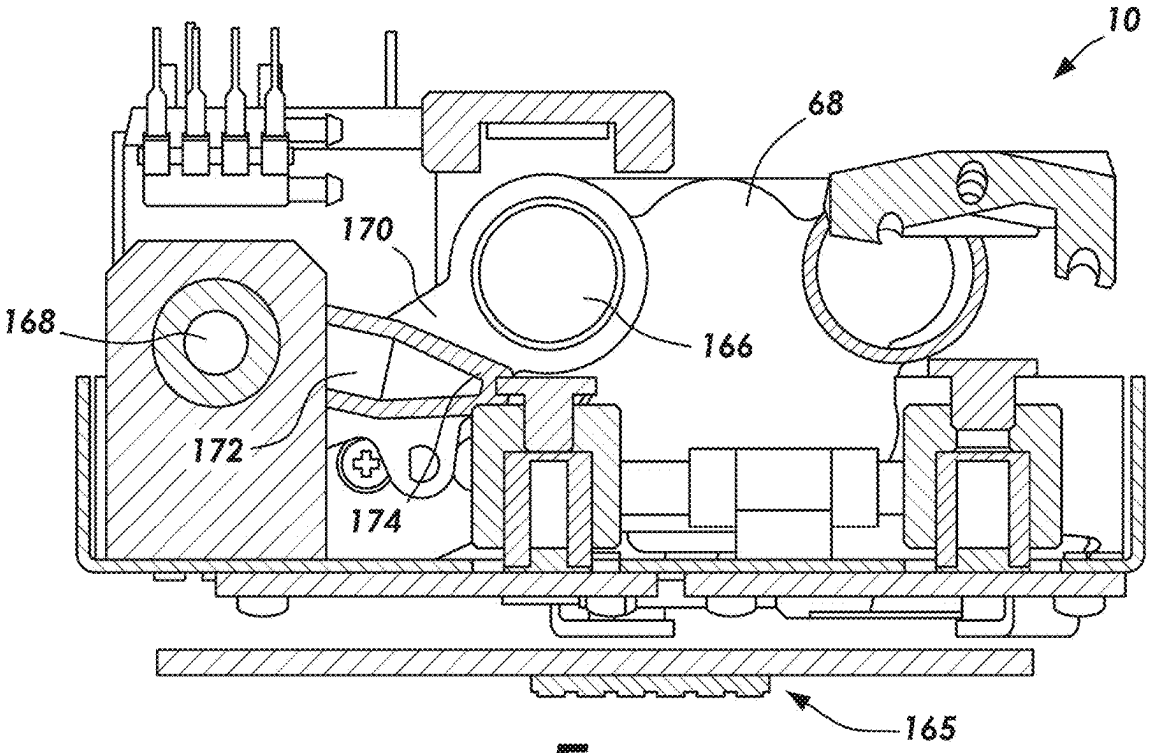


FIG. 6B

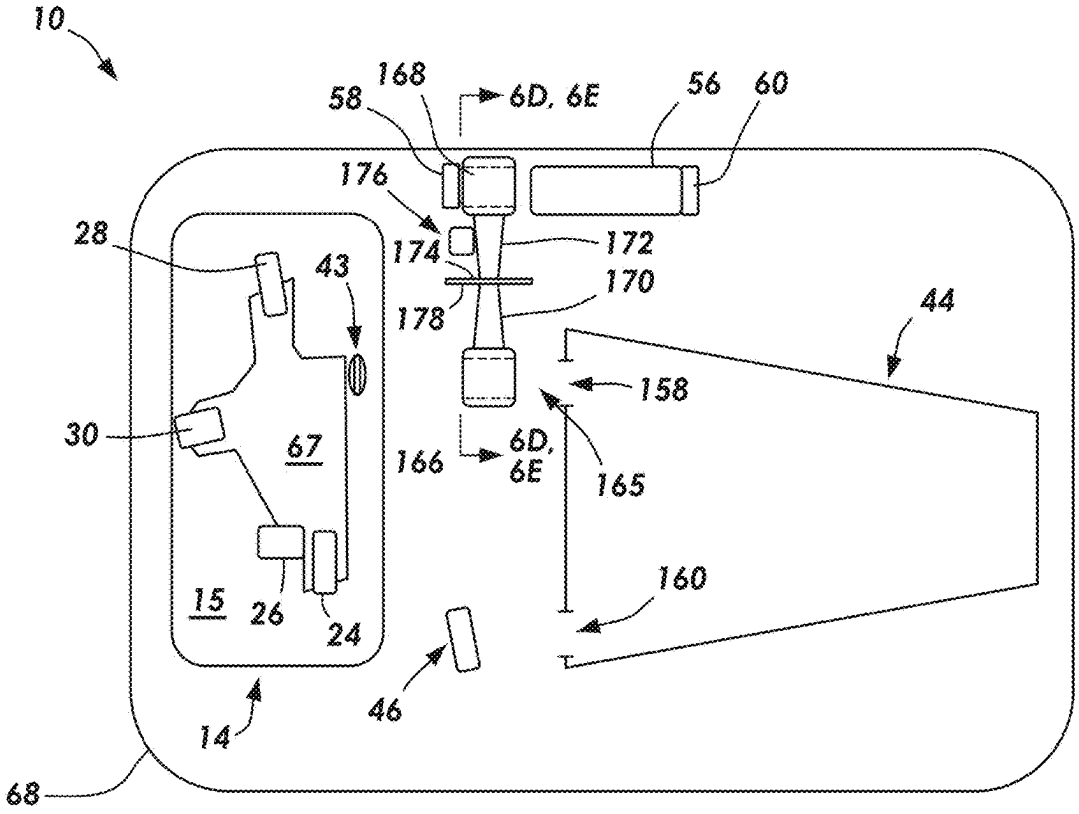


FIG. 6C

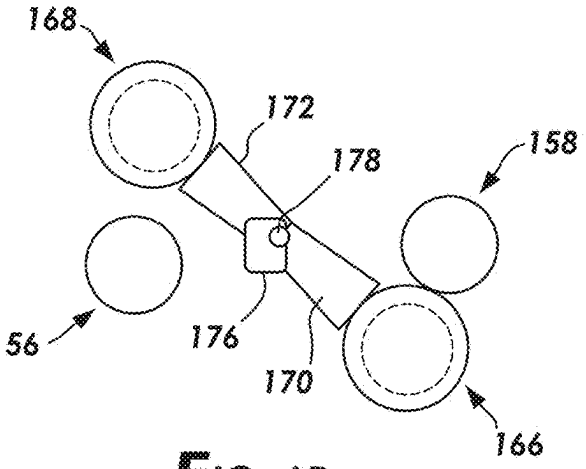


FIG. 6D

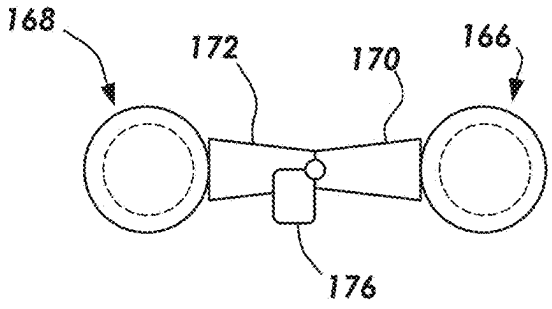


FIG. 6E

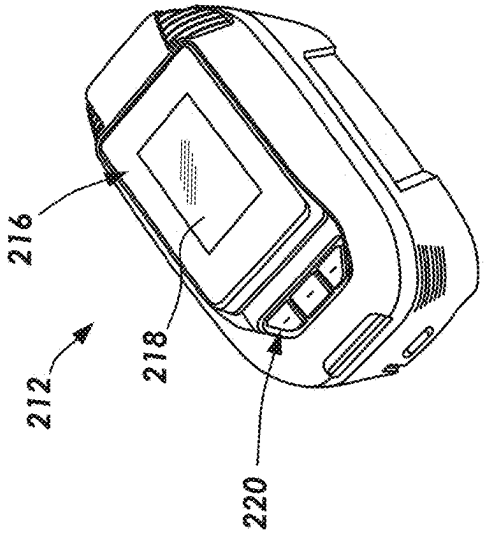


FIG. 7B

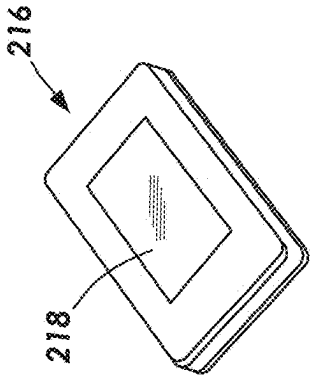


FIG. 8

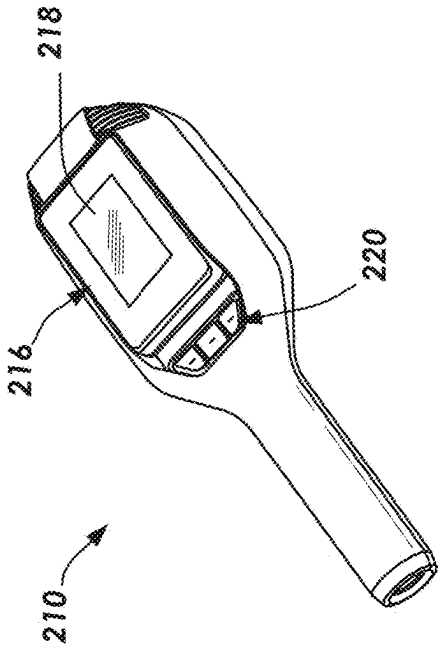


FIG. 7A

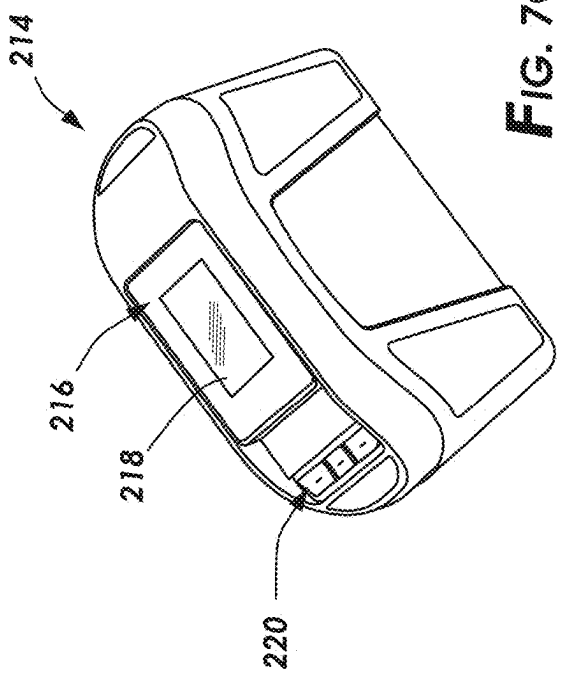


FIG. 7C

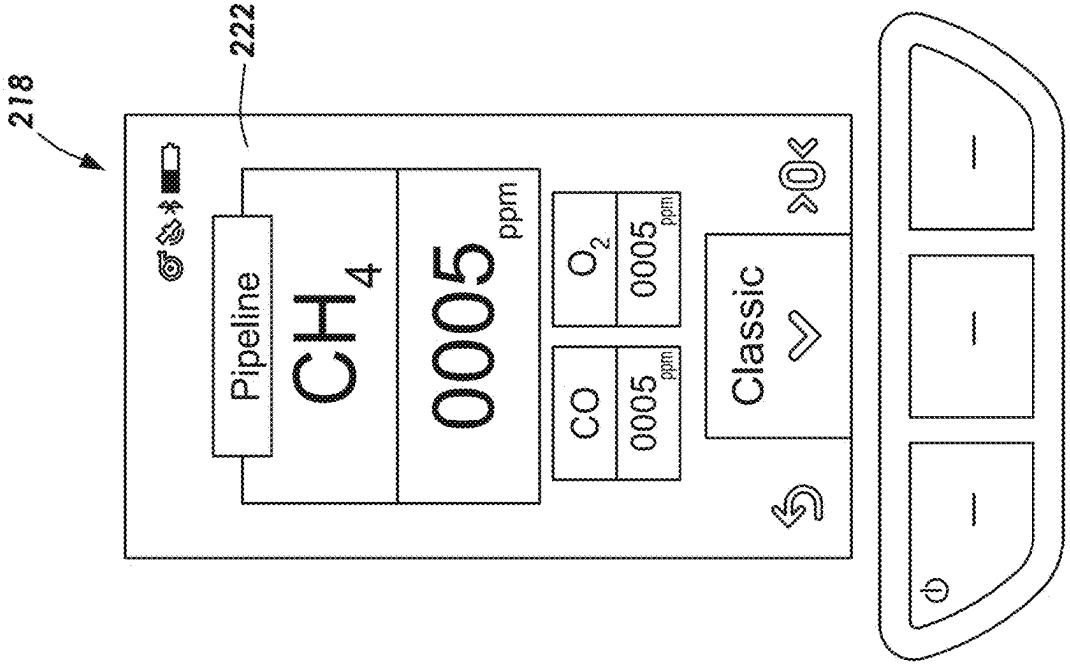

218
222
Pipeline
CH_4
0005 ppm
O_2
0005 ppm
CO
0005 ppm
Classic

FIG. 9A

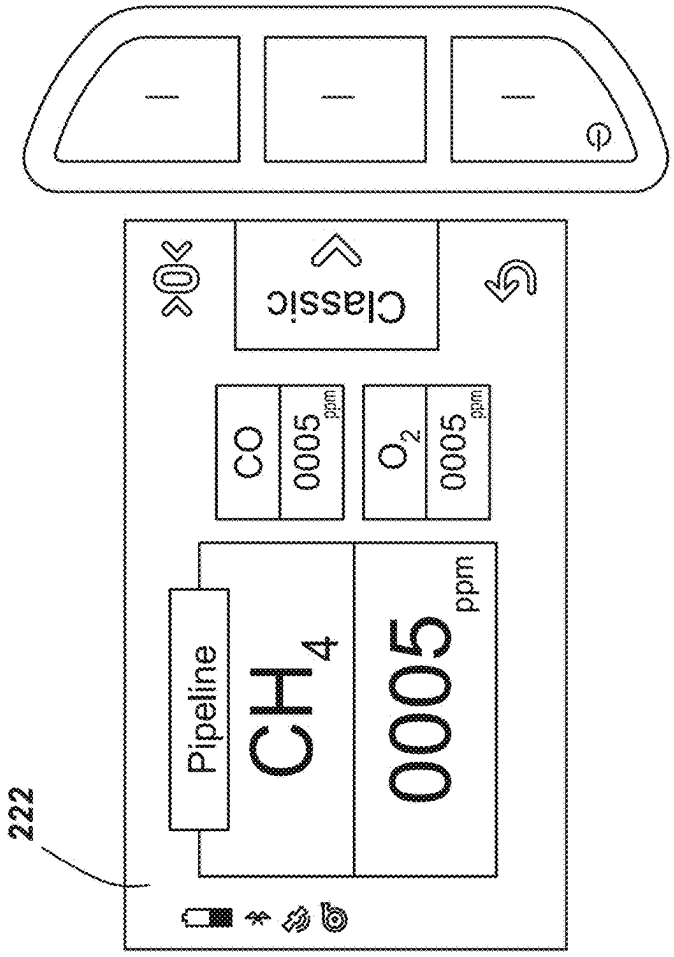

222
Pipeline
CH_4
0005 ppm
O_2
0005 ppm
CO
0005 ppm
Classic

FIG. 9B

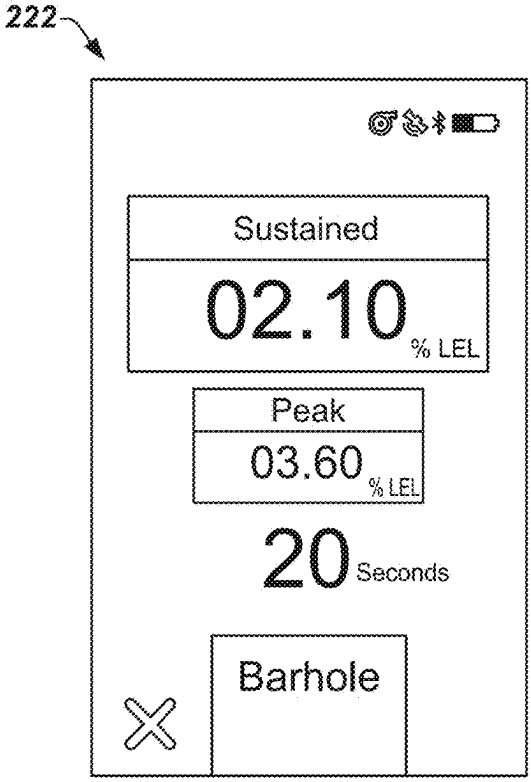


FIG. 10A

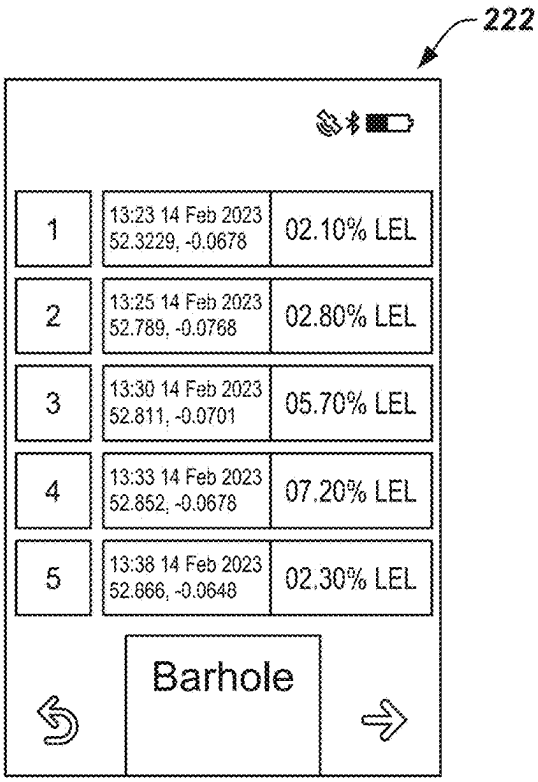


FIG. 10B

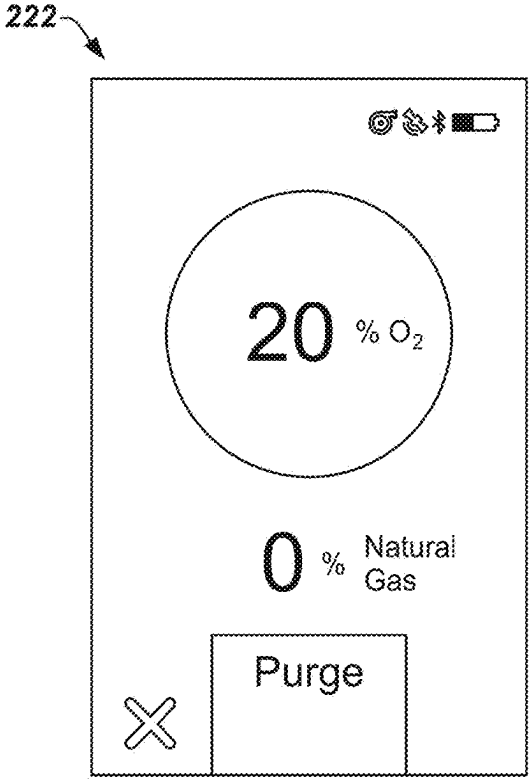


FIG. 10C

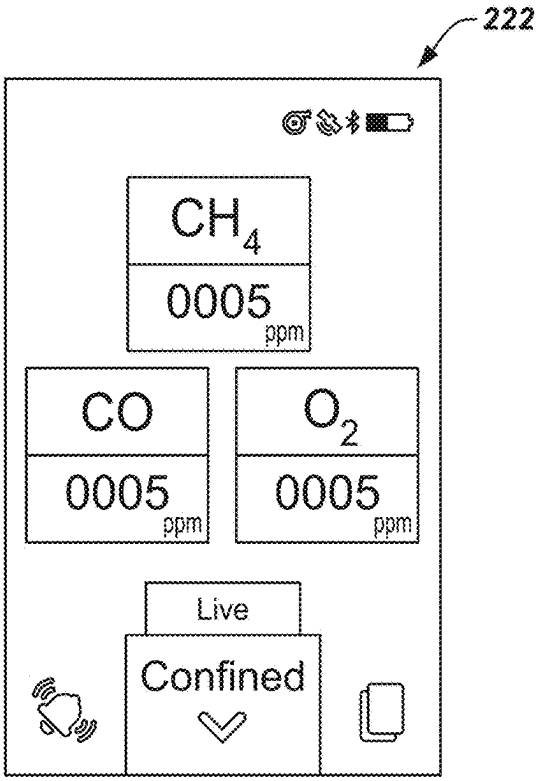


FIG. 10D

MULTI-GAS SENSING AND DETECTION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority from U.S. Provisional Application Ser. No. 63/552,978, filed Feb. 13th, 2024, and U.S. Provisional Application Ser. No. 63/552,996 filed on Feb. 13, 2024, the full disclosures of which are incorporated by reference herein in their entireties and for all purposes.

BACKGROUND OF THE INVENTION

1. Field of Invention

[0002] The present invention relates generally to a gas detection apparatus and method which utilizes the absorption of light to detect the presence of gases of interest at an extended range. The present invention uses non-dispersive infra-red (NDIR) technology.

2. Description of Prior Art

[0003] Different types of gases have unique light absorption characteristics. In other words, each gas type absorbs different optical frequencies. A gas analyzer system can utilize the unique absorption characteristics to identify whether a particular type of gas is present in a gas sample.

[0004] In the mid-infra-red range (approximately 2 μm-10 μm) many gases of interest have optical absorption bands. Methane (CH_4) has two strong broad absorption bands in the mid-IR spectral range centered at ~3.3 μm and ~7.7 μm (microns). Ethane (C_2H_6) has a strong absorption band located at 3.34 μm. Absorption bands of carbon dioxide (CO_2) are centered at 4.3, 2.7, and 2 μm. Absorption bands of carbon monoxide (CO) are centered at 2.35 and 4.66 μm.

[0005] As will be discussed below, a "gap" exists in the range of 3.8 to 4.1 μm where the light is not absorbed by the gases of interest. NDIR gas detection systems often use a reference band of 3.95 microns. Conventional gas analyzer systems typically have their own operating procedures, and calibration procedures to collect accurate data.

[0006] The Beer-Lambert law, which can be expressed as $I=I_0e^{-\sigma nl}$, generally, defines a relationship that relates the absorption of a light to properties of the material irradiated by the light a gas type present in an unknown gas sample is often identified based on the Beer-Lambert law. As different materials such as gases absorb different frequencies of light energy, by passing optical energy through a gas sample and then detecting the frequencies of optical energy that are absorbed by the gas sample, the type of gas present in the sample is determinable. Further, the amount of absorption by the sample can indicate the concentration of a specific gas.

[0007] The optical transmission of a monochromatic source through a volume of absorbing gas follows the Beer-Lambert law. U.S. Pat. No. 7,835,005 discloses a device for detecting the concentration of multiple types of gases in a sample gas by absorbance measurements of the optical signal in multiple frequency bands. U.S. Pat. No. 10,545,089 discloses a technique for distinguishing methane from hydrocarbons and natural gas by using a first, second and reference wavelengths to calculate the actual concentration of methane in a gas.

SUMMARY OF THE INVENTION

[0008] Disclosed herein is an example of a method of evaluating an environment, which includes irradiating a sample volume of the environment with light at a reference wavelength, irradiating a sample volume of the environment with light at a test wavelength, the test wavelength being a wavelength that is absorbed by an analyte gas and having an intensity that is modulated to be out of phase with an intensity of the light at the reference wavelength, sensing an intensity of the light at the reference wavelength that is transmitted through the sample volume to define a sensed reference light intensity, sensing an intensity of the light at the test wavelength that is transmitted through the sample volume to define a sensed test light intensity, comparing the sensed reference light intensity with the sensed test light intensity, and identifying the presence of the analyte gas in the environment based on the step of comparing the sensed reference light intensity with the sensed test light intensity. An example of comparing the sensed reference light intensity with the sensed test light intensity includes identifying a change over time of a difference between the sensed reference light intensity and the sensed test light intensity. In one example, the analyte gas is a first analyte gas, the light at the test wavelength is a first light, and the test wavelength is a first test wavelength, the method further includes, identifying a second analyte gas present in the sample volume of the environment by irradiating the sample volume of the environment with a second light that is at a second test wavelength, where the first light includes light generated by a first light source and the second light includes light generated by a second light source having the same characteristics as the first light source. An alternative to this example further includes forming the first light by filtering a lower portion of the bandwidth of light from the first light source, and forming the second light by filtering an upper portion of the bandwidth of light from the first light source. Further optionally, absorption bands of the first and second analyte gases overlap. In an alternative, the light at the test wavelength is a first light at the test wavelength and the test wavelength is a first test wavelength, the method further including irradiating the sample volume of the environment with a plurality of lights at a plurality of test wavelengths, each of the plurality of test wavelengths being different from the first test wavelength and being different from any of the other plurality of test wavelengths, and each of the plurality of lights having an intensity that is modulated to be out of phase with an intensity of the light at the reference wavelength. This alternative further includes controlling irradiation of the sample volume so that over a designated period of time the sample volume is irradiated with the first light at the test wavelength or one of the plurality of lights at the plurality of test wavelengths light, further options include one or more of, the sample volume being continuously irradiated with the light at the reference wavelength and each of the plurality of test wavelengths being a wavelength that is absorbed by a different analyte gas. Examples of the environment include an ambient fluid within a residential area, a landfill, a construction site, a gas distribution facility, a gas storage facility, an area where first responders have been summoned, an industrial area, a public area, any area, space or place where the presence and/or quantity of a designated substance is being sensed, detected, or measured, and combinations. In examples, the analyte gas is one or more of a noxious gas, carbon monoxide, carbon dioxide,

hydrocarbon gases, methane, or ethane. The irradiating and sensing are optionally performed using a sensing system that includes a controller for identifying the analyte gas and a reference vial having a substance in a known concentration, the method further includes calibrating the sensing system by irradiating the reference cell with the reference and test lights, sensing the intensity of the test lights being transmitted through the reference cell, and adjusting the sensed test and reference light intensities transmitted through the sample volume based on sensed intensities being transmitted through the reference cell.

[0009] Also disclosed is an example of a system for evaluating an environment, which includes a reference light source emitting a reference light having a time varying intensity, a test light source emitting a test light having a time varying intensity modulated to be out of phase with the reference light and having a wavelength that is within an absorption band of an analyte gas, a space in which a sample volume of the environment is contained, an optical system comprising, an inlet in the path of the reference light, an inlet in the path of the test light, and an exit, an emission of light comprising reference light and test light, which projects from the exit and passes through the space and the sample volume of the environment, and a sensor strategically disposed in a path of the emission of light and on a side of the space opposite the exit. In one example, the sensor is responsive to an intensity of light and the system further includes a controller configured to receive signals from the sensor representing light intensity and identify the presence of an analyte gas in the sample volume. The optical system optionally includes dichroic mirrors and collimators for collimating the reference light emitted from the reference light source and the test light from the test light source onto the dichroic mirrors, and where the collimators are supported in place by the dichroic mirrors. In one example, the test light source and test light are a first test light source and a first test light, the system further including a second test light source having the same characteristics as the first test light source, the optical system including a band pass filter having an inlet in the path of the first test light and second test light and an exit from which a modified first test light is emitted having a bandwidth that is in the upper half of a bandwidth of the first test light and a modified second test light is emitted having a bandwidth that is in the lower half of a bandwidth of the second test light, where the modified first test light is in the absorption band of a first analyte gas and the modified second test light is in the absorption band of a second analyte gas, and where the absorption bands of the first and second analyte gases overlap. Embodiments exist in which the system further includes a calibration system having an arm that is selectively pivotable and a reference vial containing an analyte gas of a known concentration, where the reference vial is coupled to the arm and selectively pivoted into the path of the emission of light. The system optionally includes a housing covering other elements of the system, a power supply in the housing, and a handle selectively held by an operator when the system is transported to and used in remote environments. In alternatives, the sample volume of the environment is contained in a gas cell comprising a container selected from the group consisting of a low concentration gas cell and a high concentration gas cell. In an example, the test light source and test light are a first test light source and a first test light, the system further having a plurality of test light sources from which a plurality of test lights are selectively emitted, where the first test light and the plurality of test lights are each sequentially emitted and are modulated to be out of phase with the reference light, and where the reference light is continuously emitted.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Some of the features and benefits of the present invention having been stated, others will become apparent as the description proceeds when taken in conjunction with the accompanying drawings, in which:

[0011] FIG. **1** is a schematic of a system for sensing analyte gases present in an environment ambient to the system. FIG. **2** is a schematic example of operation of the system of FIG. **1**.

[0012] FIGS. **2**A-**2**D are schematic examples of the optical filtering performed by the system.

[0013] FIG. **2**E is a photo of an embodiment of the source system shown in a perspective view.

[0014] FIGS. **3**A-**3**G are graphical illustrations of examples of amplitude modulation and multiplexing of light during operation of the system of FIG. **1**.

[0015] FIGS. **4** and **5** are sectional views of examples of gas cells for use with the system of FIG. **1**.

[0016] FIG. **5**A is a perspective view of components in the gas cell of FIG. **5**.

[0017] FIGS. **6**A-**6**E are side and overhead views of examples of the system in a non-calibrating mode and a calibrating mode.

[0018] FIGS. **7**A-**7**C are perspective views of example embodiments of multi-gas measurement and detection tools having the system of FIG. **1**.

[0019] FIG. **8** is a perspective view of an example of a head module for use with the multi-gas measurement and detection tools of FIGS. **7**A-**7**C.

[0020] FIGS. **9**A and **9**B are examples of orientations of displays of the head module of FIG. **8**.

[0021] FIGS. **10**A-**10**D are examples of images displayed on the head module of FIG. **8**.

[0022] While subject matter is described in connection with embodiments disclosed herein, it will be understood that the scope of the present disclosure is not limited to any particular embodiment. On the contrary, it is intended to cover all alternatives, modifications, and equivalents thereof.

DETAILED DESCRIPTION OF INVENTION

[0023] The method and system of the present disclosure will now be described more fully hereinafter with reference to the accompanying drawings in which embodiments are shown. The method and system of the present disclosure may be in many different forms and should not be construed as limited to the illustrated embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey its scope to those skilled in the art. Like numbers refer to like elements throughout. In an embodiment, usage of the term "about" includes +/−5% of a cited magnitude. In an embodiment, the term "substantially" includes +/−5% of a cited magnitude, comparison, or description. In an embodiment, usage of the term "generally" includes +/−10% of a cited magnitude.

[0024] It is to be further understood that the scope of the present disclosure is not limited to the exact details of construction, operation, exact materials, or embodiments shown and described, as modifications and equivalents will be apparent to one skilled in the art. In the drawings and specification, there have been disclosed illustrative embodiments and, although specific terms are employed, they are used in a generic and descriptive sense only and not for the purpose of limitation.

[0025] Shown in perspective view in FIG. **1** is a schematic example of a sensing system **10** for use in sensing for and detecting the presence of a fluid or fluids, such as in an example an analyte gas in a sample of gas obtained from a space or an environment ambient to the sensing system **10**. A controller/power supply ("CPS") **11** is included with the system **10**, and which provides electrical power and/or control signals to components in the system **10** via a bus **12** shown connected to CPS **11**. The bus **12** includes leads **13** shown extending to a source assembly **14** that includes an aluminum core printed circuit board ("PCB") **15**. The source assembly **14** includes a plurality of light emitting diodes ("LEDs") **16**, **18**, **20**, **22** mounted on the PCB **15** and collimators **24**, **26**, **28**, **30** are respectively disposed adjacent to the LEDs **16**, **18**, **20**, **22**, and in an example embodiment include high precision molded elliptical mirrors. Also on the PCB **15** are band pass filters **32**, **34**, which as shown are generally planar and oriented substantially perpendicular to the PCB **15**. In this example band pass filters **32**, **34** are adjacent the collimators **30**, **28**, respectively. A dichroic filter **36** is shown mounted on the PCB **15** and having a length so that it has portions adjacent each of the collimators **24**, **26**. The dichroic filter **36** is a planar member, and similar to the band pass filters **32**, **34**, is oriented substantially perpendicular to the PCB **15**. Another dichroic filter **38**, which is also planar, is shown mounted perpendicular to the PCB **15** and spaced a distance forward of the band pass filters **32**, **34** and lateral to the dichroic filter **36**. An additional dichroic mirror **40** is shown spaced forward of the dichroic filter **38**. The dichroic mirror **40** is a planar member oriented substantially perpendicular to the PCB **15** and mounted on the PCB **15**. Another bandpass filter **42** is shown provided on the PCB **15**, and perpendicular to the PCB **15** in a space laterally between the dichroic mirror **36** and dichroic mirror **40**. An output lens **43** spaced forward of the dichroic mirror **40** is mounted on the PCB **15**. Examples of the LEDs **16**, **18**, and **20** are obtainable from Hamamatsu at (hamamatsu.com), and LED **22** is obtainable from Nanoplus (Contact|nanoplus), having an optical output that is configured for the detection of carbon monoxide. In examples, the light generated by the LEDs **16**, **18**, **20**, **22** is infrared, and having a wavelength ranging from about 0.78 microns to about 1000 microns, about 2 microns to about 50 microns, about 2 microns to about 10 microns.

[0026] The sensing system **10** of FIG. **1** further includes a low concentration gas cell **44** shown spaced adjacent the PCB **15** and strategically located to be in an optical path of the output lens **43**. A photo detector **46** is shown mounted onto an end of the low concentration gas cell **44** opposite the output lens **43**. An optional beam splitter **48** is illustrated between the output lens **43** and the low concentration gas cell **44**. Spaced laterally from the beam splitter **48** is a reference detector **50**. Communication links **52**, **54** are shown respectively connected to the photo detector **46** and the reference detector **50**. Communication links **52**, **54** provide a means for selectively communicating signals, such as electrical and/or electromagnetic, between the controller **11** and photo detector **46** and/or between the controller **11** and the reference detector **50**. A high concentration gas cell **56** is included with the sensing system **10** that is spaced laterally away from an edge of the PCB **15**. The high concentration gas cell **56** is equipped with a light source **58** for emitting a light within the high concentration gas cell **56**, in examples light source **58** is a micro electrical mechanical system ("MEMS") blackbody thermal infrared source, such as that available at https://www.axetris.com. In alternatives, light source **58** is generated by one or more of the light sources described herein, and where the light generated is processed by one of the modulation schemes described below. In the illustrated example, the high concentration gas cell **56** also includes a photo detector **60** that selectively senses intensity of light emitted from the light source **58**, which reaches the end of the high concentration gas cell **56** opposite from the light source **58**. Embodiments of the photo detector **60** include a four channel pyroelectric detector, examples of which are available from Infratec at https://www.infratec.co.uk/and having channels for the detection of CH_4 (3.33 μm), CO_2, H_2O, and a reference channel. Inside the high concentration gas cell **56** is an ellipsoidal reflector with the light source **58** and detector **60** placed at the foci. Communication links **62**, **64** are shown providing communication between the controller/power source **11** and the light source **58** and photo detector **60** respectively. Examples of the communication links **52**, **54**, **62**, **64** include conductive materials, fiberoptics, means for transmitting and receiving wireless signals, and combinations.

[0027] Still referring to FIG. **1**, a thermistor **65** is shown mounted on the PCB **15** for monitoring the temperature of the PCB **15**. The thermistor **65** is selectively in communication with a thermal electric cooler **66** shown in dashed outline and mounted on a lower surface of the PCB **15**. In one example, the thermoelectric cooler **66** is a Peltier or Peltier-type cooler. Also shown in dashed outline is a support plate **67** disposed upwards from the PCB **15** on upper lateral edges of the filters **32**, **34**, **42** and/or the dichroic mirrors **36**, **38**, **40**. Further in this example, the collimators **24**, **26**, **28**, **30** are secured onto the support plate **67** and suspended in precise locations and orientations with respect to the LEDs **16**, **18**, **20**, **22**. An advantage of this arrangement is that the source assembly **14** is a thermally stable unit, and its performance and output accuracy is not degraded when subjected to expected operating temperatures, as in examples, members supporting the plate **67** above the board **15**, i.e., one or more of filters **32**, **34**, **42** and mirrors **36**, **38**, **40** are formed from a silicon based material that does not expand or contract in size by an amount that affects or disturbs a precise alignment between the LEDs **16**, **18**, **20**, **22** and the collimators **24**, **26**, **28**, **30**. Advantages also exist by the use of silicone and other materials having a high coefficient of thermal conductivity, which quickly transfers heat so that thermal effects are not experienced due to disparate thermal expansion in different components.

[0028] A housing **68**, illustrated in dashed outline in FIG. **1**, surrounds the controller/power supply **11**, gas cells **44**, **56**, and source assembly **14** separating these components from ambient fluid **70** that makes up the environment surrounding the sensing system **10**. In an embodiment, a sample volume, such as the ambient fluid **70**, is obtained from the environment, which in alternatives is obtained using the sensing

system **10** or any other sampling device. In examples, the sensing system **10** is a handheld portable device, manually operated by an individual for testing the ambient fluid **70** for a designated substance(s), such as an analyte gas **71**. Testing the ambient fluid **70** includes investigating, sensing, detecting, and/or identifying the presence and quantity of the designated substance in the ambient fluid **70**. Examples of the ambient fluid **70** include ambient air in a particular space within an area, such as a residential area, a landfill, construction site, gas distribution facility, gas storage facility, an area where first responders have been summoned, an industrial area, a public area, or at any area, space or place where the presence and/or quantity of a designated substance is being sensed, detected, or measured. Specific examples of analyte gas **71** include noxious gases, such as carbon monoxide, carbon dioxide, and hydrocarbon gases, including but not limited to methane and ethane. In a non-limiting example of use, an amount of ambient fluid **70** from ambient is drawn into the housing **68** through a line **72** where it is directed to the high concentration gas cell **56** and discharged from the high concentration gas cell **56** through a line **73**. Similarly, ambient fluid **70** to be analyzed in the low concentration gas cell **44** is drawn to the low concentration gas cell **44** through a line **74** and discharged from the low concentration gas cell **44** through a line **75**. Openings **76**, **77**, **78**, **79** penetrate through the housing **68** to provide communication between ambient and lines **72**, **73**, **74**, **75**.

[0029] Examples of operation of the sensing system **10** include manually transporting the system **10** to a particular space where ambient fluid **70** is to be tested. The ambient fluid **70** is drawn into the cells **44**, **56** where it is illuminated with light. Light from the light source **58** irradiates the fluid **70** in the high concentration gas cell **56**, and as explained in more detail below, light from the LEDS **16**, **18**, **20**, **22** is captured, focused, imaged, and filtered through the components in the system **10**, and then directed to the high concentration cell **56** where it illuminates the fluid **70** in the low concentration gas cell **44**. The presence and amount of the analyte gas **71** in the cells **44**, **56** is estimated by measuring an amount of optical absorption of light emitted into the cells **44**, **56**. In an example, a particular analyte is identified inside the cells **44**, **56** by emitting light into the cell(s) **44**, **56** having a wavelength that is within an optical absorption band of the particular analyte, and an absorption of that light is detected within the cell(s) **44**, **56**. Examples of detecting absorption include comparing an intensity of light emitted into the cells **44**, **56** with an intensity of light sensed by the photodetectors **46**, **60**. Optionally, software in or accessed by controller/power supply **11** provides instructions for this comparison. In one example of operation, the LEDs **16**, **18**, **20**, **22** are energized in a time modulated fashion so that a magnitude of light output from one of the LEDs **16**, **18**, **20**, **22** is out of phase with the other LEDs **16**, **18**, **20**, **22**. The light output that is out of phase is referred to as a reference light, and lights from the LEDs that are in phase with one another and out of phase with the reference light are referred to as test lights. Embodiments exist in which the phase difference between the reference light and each of the test lights ranges up to about 180°. In an alternative, the reference light is at a wavelength outside optical absorption bands of analyte gases to be detected, and test light wavelengths are within optical absorption bands of analyte gases to be detected. As described in more detail below, the reference light and one or more of test lights simultaneously irradiate the low concentration gas cell **44**, and the intensity of the reference and test lights are measured by the photodetector **46**. In examples in which none of the test lights is absorbed by gas in the low concentration gas cell **44** (and thus the wavelengths of the test lights are all outside of the optical band of gas in the low concentration gas cell **44**), because the intensity of the reference and test lights are time varying and out of phase, the photodetector **46** generates an output signal that is substantially constant. In examples in which one or more of the test lights is absorbed by gas in the low concentration gas cell **44** (e.g., one or more of the wavelengths of the test lights are within an optical band of a gas in the low concentration gas cell **44**), that output signal from photodetector **46** is not constant over time, but changes when the test light is absorbed by one of the gases inside the low concentration gas cell **44**.

[0030] Referring now to FIG. **2**, a nonlimiting example of use of the sensing system **10** is shown in which the LEDs **16**, **18**, **20**, **22** are selectively energized to emit light, which is optically filtered for spectroscopic analysis of the ambient fluid **70** within the low concentration gas cell **44**. In this example, energizing LED **16** generates light **80**, a portion of light **80** is focused by the collimator **24** into focused light **84**, which is directed towards dichroic filter **36**. Similarly, energizing LED **18** generates light **82**, and a portion of light **82** is redirected and focused by collimator **26** to create focused light **86**, which is directed towards dichroic filter **36**. Focused light **84** passes through and is filtered by dichroic filter **36** to create light $\mathbf{88}_1$ and focused light **86** is reflected by and filtered by dichroic filter **36** to create light $\mathbf{88}_2$, light $\mathbf{88}_{1,2}$ is shown being directed towards the bandpass filter **42**. Light $\mathbf{88}_{1,2}$ is filtered by bandpass filter **42**, which exits as light $\mathbf{90}_{1,2}$ and directed towards dichroic mirror **40**. The bandwidths of light $\mathbf{90}_{1,2}$ are narrower than light $\mathbf{88}_{1,2}$, having been narrowed by bandpass filter **42**.

[0031] Energizing LED **20** creates light **92** shown directed towards collimator **28**, where it is refocused and reimaged as light **94** shown being directed towards the bandpass filter **34**, and light **96** exiting the opposite side of bandpass filter **34** is directed towards dichroic mirror **38**. Energizing LED **22** generates light **98** shown being directed towards collimator **30**, which is reimaged and refocused as light **100** that is directed to the bandpass filter **32**. Light **100** is filtered by bandpass filter **32** and exits the opposing surface of bandpass filter **32** as light **102** that is directed to dichroic mirror **38**. Light **102** passes through and is filtered by dichroic filter **38** to form light $\mathbf{104}_1$ shown exiting a side of dichroic filter **38** opposite bandpass filter **32** and being directed to dichroic mirror **40**. Light **96** is reflected and filtered by dichroic filter **38** and exits filter **38** as light $\mathbf{104}_2$ being directed towards dichroic filter **40**. In this example, light $\mathbf{104}_2$ is the reference light, which is emitted simultaneously with each light $\mathbf{90}_1$, light $\mathbf{90}_2$, and light $\mathbf{104}_1$, whereas light $\mathbf{90}_1$, light $\mathbf{90}_2$, and light $\mathbf{104}_1$ are emitted sequentially and not simultaneous to one another. Further in this example, light $\mathbf{104}_1$ and light $\mathbf{104}_2$ are combined and transmitted through dichroic filter **40** to create light $\mathbf{106}_1$, light $\mathbf{104}_2$ and light $\mathbf{90}_1$ are combined and reflected by dichroic filter **40** to create light $\mathbf{106}_2$, and light $\mathbf{104}_2$ and light $\mathbf{90}_2$ are combined and reflected by dichroic filter **40** to create light $\mathbf{106}_3$. Each of light $\mathbf{106}_{1\text{-}3}$ are shown extending from a surface of dichroic mirror **40** towards output lens **43**. Light $\mathbf{108}_{1\text{-}3}$ represents light $\mathbf{106}_{1\text{-}3}$ being refocused by lens **43** which intersects the beam splitter **48** and exits as light $\mathbf{110}_{1\text{-}3}$, which enters the low concen-

tration gas cell **44**. Collimators **24**, **26**, **28**, **30**, dichroic mirrors **36**, **38**, **40**, band pass filters **38**, **42**, and lens **43** define an optical system **111**. A portion of light $\mathbf{108}_{1\text{-}3}$ is redirected by the beam splitter **48** as light $\mathbf{112}_{1\text{-}3}$ to the reference detector **50**. In an example, the amount of light $\mathbf{112}_{1\text{-}3}$ is a small percentage of light $\mathbf{108}_{1\text{-}3}$, which optionally ranges up to around 3% of light $\mathbf{108}_{1\text{-}3}$. The light $\mathbf{112}_{1\text{-}3}$ received by the reference detector **50** generates signals which are sent via the communication link **54** to the controller **11**, and analyzed to confirm a stable and proper output from the LEDs **16**, **18**, **20**, **22**, this provides information to account for any drift from a baseline signal. An advantage of the beam splitter **48** and reference detector **50** is to provide a constant output from the LEDs **16**, **18**, **20**, **22** and stabilize the output of any of the nondispersive infrared sources. In an alternative the reference detector **50** samples light $\mathbf{112}_{1\text{-}3}$ at about every 50 microseconds.

[0032] Schematically illustrated in FIG. **2**A is an example of the optical filtering of the light generated by the LEDs **16**, **18**, **20**, **22**. In this example, LED **20** is a reference light source and produces a reference light and LEDs **16**, **18**, **22** are test light sources that each generate a test light, in alternatives, each test light is in a wavelength of interest to identify analyte gas **71**. As described in more detail below, LEDs **16**, **18**, and **22** are multiplexed, i.e., each is operated at specific sequences of time while at the same the other two are not operating and not generating a test light. The LED **20** operates simultaneously with each sequence of test light generation by LEDs **16**, **28**, **22** so that the reference light is generated coincident with and during generation of each of the test lights. An advantage of this operation is that comparing a signal representing characteristics of each test light generated by one of LEDs **16**, **18**, **22** with a signal representing characteristics of the reference light generated by LED **20**, the presence of an analyte gas **71** within the ambient fluid **70** is detectable. In an embodiment, the signals being compared are output signals from the photodetector **46** and/or detector **60**. In this example, LED **16** and LED **18** have substantially the same construction and specifications so that lights **80**, **82** (FIG. **2**) emitted respectively from LEDs **16**, **18** have substantially the same signatures and the light generated by and emitted from these LEDs **16**, **18** have substantially the same characteristics, such as wavelength, a spatial profile, and an angular profile. Dichroic filter **36** is configured so that light **84** from collimator **24** passes through and is filtered by filter **36** to form light $\mathbf{88}_1$. Light **86** from collimator **26** is filtered by and reflected from dichroic filter **36** to create light $\mathbf{88}_2$. As light **84** and light **86** have substantially the same characteristics, the filtering by dichroic filter **36** modifies light **84** and light **86** and results in a modified light $\mathbf{88}_2$ having a bandwidth that is on a lower half of the bandwidth of light **86**, and conversely results in a modified light $\mathbf{88}_1$ having a bandwidth that is on an upper half of the bandwidth of light **84**. In this example, LEDs **16** and **18** are energized to operate sequentially and without their respective periods of operation overlapping, light **84** and light **86** reach filter **36** along different time periods so that light $\mathbf{88}_1$ and light $\mathbf{88}_2$ are not present at the same time. Downstream of dichroic filter **36**, bandpass filter **42** receives light $\mathbf{88}_1$ and filters and modifies light $\mathbf{88}_1$ to form a narrower bandwidth light $\mathbf{90}_1$. In an alternative, a pair of bandpass filters (not shown) are upstream of dichroic filter **36** instead of the single bandpass filter **42** being downstream of dichroic filter **36**. Similarly, light $\mathbf{88}_2$ is further modified by passing through bandpass filter **42** to form light $\mathbf{90}_2$ which is at a smaller bandwidth than light $\mathbf{88}_2$. Light $\mathbf{90}_1$ and light $\mathbf{90}_2$, which are shown collectively as $\mathbf{90}_1$,**2** are sequentially directed towards dichroic mirror **40** that is angled with respect to the direction of light $\mathbf{90}_1$ and light $\mathbf{90}_2$.

[0033] Still referring to FIG. **2**A, light **100** being emitted from LED **22** and collimator **30** passes through bandpass filter **32** to form light **102**, which has a smaller bandwidth than light **100**. Similarly, light **94** being emitted from LED **20** and collimator **28** passes through bandpass filter **34** to form light **96** that has a smaller bandwidth than light **94**. Bandpass filters **32**, **34**, and **42** of FIG. **2**A are configured to remove light outside of a designated bandwidth, an example of a designated bandwidth includes an absorption band of an analyte gas. An advantage of narrowing a bandwidth of light to a designated bandwidth avoids cross-talk in a sensor, such as a photodetector, when detecting the light. Dichroic filter **38** is angled so that light **102** is transmitted through dichroic filter **38** to form light $\mathbf{104}_1$ shown being directed towards dichroic filter **40**. Dichroic filter **38** is also configured so that light **96** exiting bandpass filter **34** is reflected from dichroic filter **38** to form light $\mathbf{104}_2$ also shown being directed towards dichroic filter **40**. In this example, LED **20** is operated substantially continuously to create the reference signal discussed above and LEDs **16**, **18**, **22** are energized sequentially and not simultaneously to generate test signals. As described above, collimators **24**, **26**, **28**, **30** collimate light **80**, **82**, **92**, **98** to respectively form light **84**, **86**, **94**, **100**; and the light **80**, **82**, **92**, **98** is generated respectively by LEDs **16**, **18**, **20**, **22**, where LED **20** operates continuously, while LEDs **16**, **18**, **22** do not operate simultaneously, but instead operate sequentially in a first, second, and third time period or sequence.

[0034] Shown schematically in FIGS. **2**B-**2**D is a non-limiting example of operation of the source tree **14** during the first, second, and third respective time periods or sequences and the light being generated and processed during these sequences. During each of the first, second, and third sequences, LED **20** operates and generates light **92** (FIG. **2**). Light **92** passes through the collimator **28** to form light **94** that transmits through bandpass filter **34** to form light **96**, which reflects from dichroic mirror **38** to form light $\mathbf{104}_2$, Light $\mathbf{104}_2$ is directed from dichroic mirror **38** to a side of dichroic mirror **40**.

[0035] In FIG. **2**B, shown is a schematic example of the first time period or sequence, during which LED **18** operates to generate light **82** (FIG. **2**) while LEDs **16** and **22** are not operating. Light **86** from collimator **26** reflects from dichroic mirror **36** to form light $\mathbf{88}_2$, which is processed by bandpass filter **42** into a narrower bandwidth light $\mathbf{90}_2$ and directed to a side of dichroic mirror **40** opposite light $\mathbf{104}_2$. Light $\mathbf{90}_2$ and light $\mathbf{104}_2$ are combined by dichroic mirror **40** into light $\mathbf{106}_1$ shown directed to an upstream side of lens **43**. Light $\mathbf{106}_1$ is focused by lens **43** into light $\mathbf{108}_1$ and transmitted from a downstream side of lens **43** to gas cell **44**. Light $\mathbf{106}_1$ passes through gas cell **44** where it is detected by photodetector **46**, which emits a signal representative of the intensity of light $\mathbf{108}_1$ sensed by the photodetector **46**.

[0036] An example of the second time period or sequence is shown schematically in FIG. **2**C, during the second time period LED **16** operates to generate light **80** (FIG. **2**), and LEDs **18** and **22** are not operating. Light **80** is collimated by collimator **24** into light **84** that is directed to dichroic mirror **36**, and exits dichroic mirror **36** as light $\mathbf{88}_1$, which is

processed by bandpass filter **42** into a narrower bandwidth light $\mathbf{90}_1$ and directed to a side of dichroic mirror **40** opposite that receiving light $\mathbf{104}_2$. Light $\mathbf{90}_1$ and light $\mathbf{104}_2$ are combined by dichroic mirror **40** into light $\mathbf{106}_2$, which similar to light $\mathbf{106}_1$ is directed to an upstream side of lens **43**. Light $\mathbf{106}_2$ is focused by lens **43** into light $\mathbf{108}_2$ that is transmitted from a downstream side of lens **43** to gas cell **44**. Light $\mathbf{108}_2$ passes through gas cell **44** where it is detected by photodetector **46**, which emits a signal representative of the intensity of light $\mathbf{108}_2$ sensed by the photodetector **46**. An example of the third time period or sequence is shown in FIG. **2**D, during the third sequence LED **22** operates to generate light **98** (FIG. **2**), and LEDs **16** and **18** are not operating. Light **98** is collimated by collimator **30** into light **100** that is directed towards and passes through bandpass filter **32** to form light **102** having a bandwidth narrower than that of light **100**. Light **102** is directed through dichroic mirror **38** and exits as light $\mathbf{104}_1$ and is directed to the same side of dichroic mirror **40** that receives light $\mathbf{104}_2$. Light $\mathbf{104}_1$ and light $\mathbf{104}_2$ are combined by dichroic mirror **40** into light $\mathbf{106}_3$ shown directed to an upstream side of lens **43**. Light $\mathbf{106}_3$ is focused by lens **43** into light $\mathbf{108}_3$ and transmitted from a downstream side of lens **43** to gas cell **44**. Light $\mathbf{108}_3$ passes through gas cell **44** where it is detected by photodetector **46**, which emits a signal representative of the intensity of light $\mathbf{108}_3$ sensed by the photodetector **46**.

[0037] As described further below and illustrated in FIGS. **3**A-**3**G, during each of the sequences output signals from the photodetector **46** are monitored, and when the output signal is substantially constant (alternatively referred to herein as "direct current"), it is determined there is no analyte gas present in the gas cell **44** having an absorption band coincident with a test signal being generated, transmitted, or processed during the particular sequence. Conversely, if during a particular time period or sequence, the output signal varies over time (alternatively referred to herein as "alternating current"), it is determined there is an analyte gas present in the gas cell **44** having an absorption band coincident with the test signal being generated, transmitted, or processed during the particular sequence.

[0038] An optional embodiment of the source system **14** is shown in a perspective view in FIG. **2**E, a reference coordinate system is included having axes in the X, Y, and Z directions. In the embodiment shown, collimator **30** is made up of a body **113** having an ellipsoid section **114** with a major axis generally aligned with the Y axis and a minor axis generally aligned with the Z axis. A face **115** is defined where a portion of outer surface ellipsoid section **114** is generally planar, face **115** has a generally elliptical outer perimeter with a minor axis generally aligned with the Z axis and a major axis oblique to the Y axis. Body **113** includes a neck section **116** that is integrally formed onto an end of ellipsoid section **114** opposite inlet aperture. Neck section **116** has a generally rectangular cross section, and a length and height generally aligned with the X and Y axes respectively, and a width oblique with the Z axis. Neck section **116** inserts into a slot **117** formed in support plate **67**, slot **117** has a length, height, and width generally aligned with that of neck portion **116**, and the length and width of slot **117** are dimensioned to receive and secure neck portion **116** within so that collimator **30** is supported a designated distance from board **15** and LED **22**, and maintained in position so that an inlet aperture (not shown) formed on a lower end of body registers with light **98** (FIG. **2**) emitted from LED **22**. A gold coated ellipsoidal mirror (not shown) is molded within ellipsoid section **114** of body **113**. Collimated light exits collimator **30** through an outlet aperture (not shown) formed through an outer surface of body **113** opposite face **115**. In the illustrated embodiment, while the orientation and/or location of collimators **24**, **26**, **28**, **30** can vary, their shape, construction, and operation are the same or substantially the same as collimators. Accordingly, the details of collimator **30** provided above are applicable to that of collimators **24**, **26**, **28**. Adhesive is optionally applied to secure the collimators **24**, **26**, **28**, **30** to the support plate **67**. Collimators **26**, **30** are oriented so that light being focused by and directed from collimator **26** is substantially parallel to light being focused by and directed from collimator **30**, but perpendicular to light being focused by and directed from collimators **24**, **28**; and light being focused by and directed from collimators **24**, **28** projects parallel and in opposite directions. Also shown is that the collimators **24**, **26**, **28**, **30** are spaced outside of the collection of the dichroic filters **36**, **38** and the band pass filter **34**. Further illustrated is that the dichroic filters **36**, **38** and band pass filter **34** are generally planar members disposed on an upper surface of PCB **15** and perpendicular to PCB **15**, and support plate **67**, which is substantially parallel to PCB **15**, is set on edges of dichroic filters **36**, **38** and band pass filter **34** distal from PCB **15**. As shown, the structure of dichroic filters **36**, **38** and band pass filter **34** provide support on which the support plate **67** mounts to the PCB **15**.

[0039] Graphically illustrated in FIGS. **3**A-**3**F are examples of amplitude modulation and multiplexing, or sequencing (alternatively referred to herein as a modulation scheme), of the light and light sources discussed above. Included in FIG. **3**A is a chart **120** which is made up of plots **122**, **124**, **126**, **128** which each have a respective ordinant **130**, **132**, **134**, **136** and an abscissa **138**, **140**, **142**, **144**. Each ordinant **130**, **132**, **134**, **136** represents an amplitude of the intensity or power of each light **84**, **86**, **94**, **100**. Included with each of the plots **122**, **124**, **126**, **128** are graphs **146**, **148**, **150**, **152** illustrating an example of time varying magnitudes of electrical power provided to the LEDs **16**, **18**, **20**, **22** for generating lights **84**, **86**, **94**, **100**. Graph **152** represents the output signal of light **92** generated by energizing LED **20**, which is shown having a continuous periodic wave form and with a time varying amplitude A_{152}, but with repeating maximum amplitude $AMAX_{152}$ and minimum amplitude $AMIN_{152}$. In the example shown, the wave form of graph **152** generally follows a sine wave function, and having a maximum amplitude substantially equal to maximum amplitudes of each of graphs **146**, **148**, **150**, so that in this example the maximum intensities of lights generated by LEDs **16**, **18**, **20**, **22** are all substantially equal. Optionally, the LEDs **16**, **18**, **20**, **22** are operated to follow other forms of repeating periodic waveforms, including but not limited to, square waves, triangular waves, complex waves, asymmetric waves, and combinations. Graphs **146**, **148**, **150** as shown also have periodic wave forms that are each 180° out of phase with the graph **152** of the reference signal. The wave forms of graphs **146**, **148**, **150** reflect the sequential operation of LEDs **22**, **16**, **18**, respectively, and as such are not continuous, but have portions that are time varying and portions where the amplitude is constant over multiple time spans. More specifically, graph **146** is time varying over time period t_2-t_3, graph **148** is time varying over time period t_1-t_2, and graph **150** is time varying over

time period t_o-t_1 and time period t_3-t_{3+}, but these graphs **146**, **148**, **150** are otherwise constant over time with amplitudes equal to their corresponding ordinates **138**, **140**, **142**. In a nonlimiting example, each of light $\mathbf{90}_1$, $\mathbf{90}_2$, $\mathbf{104}_1$ is at a wavelength within the optical absorption band of an analyte **71** (FIG. **1**) of interest within the sample of ambient gas **70** in the low concentration gas cell **44**, in which the analytes of interest are methane, ethane, and carbon monoxide. In this example, the wavelength of light $\mathbf{90}_2$ ranges from about 3160 nm to about 3285 nm with a center at about 3227 nm—which is within the optical absorption band of methane, the wavelength of light $\mathbf{90}_1$ ranges from about 3285 nm to about 3410 nm with a center at about 3322 nm, which is within the optical absorption band of ethane, the wavelength of light $\mathbf{104}_1$ is within the optical absorption band of carbon monoxide, and the wavelength of light $\mathbf{104}_2$ is outside the optical absorption bands of the analytes of interest. Further in this example, the time varying modulation of the LEDs **16**, **18**, **20**, **22** results in the intensity of light $\mathbf{104}_2$ varying in magnitude as illustrated by graph **152**, similarly, the intensity of light $\mathbf{104}_1$ also varies in magnitude as illustrated by graph **146** over time period t_o-t_1 and 180° out of phase with graph **152**. As such, in examples in which an output of a signal from the photodetector **46** is substantially constant over time period t_o-t_1 or t_3-t_{3+} indicates that gases having an absorption band corresponding to the wavelength light $\mathbf{104}_1$ are not present in the low concentration gas cell **44**; in contrast, when the photodetector **46** signal output changes over that time period, indicates a portion of light $\mathbf{104}_1$ was absorbed by a gas in the low concentration gas cell **44**, and based on the respective bands of the optical absorption band of carbon monoxide and the wavelength of light $\mathbf{104}_1$, it is deduced that the analyte fluid **70** includes carbon monoxide. Similarly, amounts of methane being present in the low concentration gas cell **44** is deduced by noticing a change in magnitude of the photodetector **46** signal over time periods t_1-t_2 when gas cell **44** is being irradiated by light $\mathbf{106}_2$, and amounts of ethane being present in the gas cell **44** is deduced by noticing a change in magnitude of the photodetector **46** signal over time periods t_2-t_3 when cell **44** is being irradiated by light $\mathbf{106}_3$. In an embodiment, the frequency of the modulation is 1 kilohertz and the span of each of the time periods t_1, t_2, t_3, etc. is 1 millisecond. An unexpected advantage realized by the placement and orientation of dichroic mirror **36** and bandpass filter **42** is the ability to generate light $\mathbf{90}_1$ and light $\mathbf{90}_2$ that when combined with light $\mathbf{104}_2$, and directed into the low concentration gas cell **44**, provides resulting output signals from the photodetector **46** that distinguish the amount and presence of methane from the amount and presence of ethane in the sample of ambient fluid **71** in the low concentration gas cell **44**. Sequencing light from LEDs **16**, **18**, **22** provides an advantage of simultaneously detecting multiple gases in cell **44**, **56**, and identifying if one of more of those gases **71** are present in the ambient fluid **70** and therefore in the environment.

[0040] Graphically shown in chart **120**A of FIG. **3**B is an example of operation similar to that of FIG. **3**A, e.g., the drive scheme steps through three drive periods, one for each test channel, and then repeats. Within one drive period, each target channel LED **16**, **18**, **22** is amplitude modulated, with the reference LED **20** modulated with the opposite signal (180 degrees out of phase). In examples of drive schemes, the reference LED **20** is modulated so that without any optical absorption of light generated by LEDs **16**, **18**, **22** in gas cell **44**, **56**, an output at a detector **46**, **60** is substantially direct current, i.e., has a substantially constant output over time because the differences between detected intensities of the reference light and test lights are constant. An alternative mode of operation is illustrated in FIGS. **3**C and **3**D in which an amplitude A**152**B of graph **152**B and an amplitude A**152**C of graph **152**C changes over time (by varying electrical power supplied to LED **20**) to be equal to or substantially the same as amplitudes of graphs **146**B, **148**B, **150**B during their respective periods of operation. An advantage of modulating electrical power supplied to the reference LED **20** provides a way of accounting for differences in power output of LEDs **16**, **18**, **22**. FIG. **3**D, like FIG. **3**A, illustrates an example of modulating over a single period for each test signal. Demonstrated in FIGS. **3**E and **3**F are ways to modulate multiple LEDs simultaneously and detect the results. The scheme shown in FIG. **3**E is referred to herein as a quadrature drive scheme, and in which LEDs **16** and **18** are time modulated to be **900** out of phase (as illustrated by the 90° offset between graphs **148**C and **150**C). In the chart **120**E depicted in FIG. **3**F, modulation occurs at different frequencies, e.g., LED **16** and **18** (for detecting methane and ethane respectively) are modulated approximately 90° out of phase with one another (graphs **148**E, **150**E), and at twice the frequency of LED **22** (graph **146**E). In further alternatives, outputs from LEDs **16**, **18**, **20**, **22** are modulated at frequencies to minimize the possibility of crosstalk due to nonlinearities in the system producing higher harmonic oscillations of a base band. Referring to FIG. **3**G, an alternative example of operation is illustrated in chart **120**F that is based on sets of digital vectors which can be used as a set of basis functions to multiplex a set of digitally modulated signals, for example Walsh functions (https://en.wikipedia. org/wiki/Walsh_function). Graphs **146**F, **148**F, **150**F show the result of using the three non-DC vectors of an order **4** Hadamard matrix (https://en.wikipedia.org/wiki/Hadamard matrix) to drive the three test LEDs **22**, **18**, **16** respectively. Other Walsh functions will also work, for example the Hadamard-Paley matrix (https://en.wikipedia.org/wiki/Paley construction).

[0041] Referring now to FIG. **4**, shown in a side section view is an example of the high concentration gas cell **56** with the light source **58** on one end. In this example, light **154** is emitted from the light source **58** into an elongated chamber inside the gas cell **56**, which includes a sample of ambient liquid **71**. The light **154** is shown reflecting from an inner surface **156** of the high concentration gas cell **56**. The inner surface **156** of the gas cell **56** is elliptical and configured so that the light **154** reflecting from surface **156** is directed to the photo detector **60** at the opposing end of the gas cell **56**. Sampled amounts of the ambient fluid **70** enter gas cell **56** through an inlet **72** and exit the cell **56** through an outlet **73** formed radially through sidewalls of the gas cell **56**, so that in cell **56** and cell **44** (FIG. **2**) is a space in which a sample volume of the ambient environment is contained. An advantage of including low and high concentration gas cells **44**, **56** in the system **10** (FIG. **1**) enables detection of a particular analyte gas with the low concentration gas cell **44** when the analyte gas is more dilute in the ambient fluid **70** and at a location distal from a source of the analyte gas, and when proximate the source of the analyte gas, the analyte gas is monitored using output from the high concentration gas cell **56**. Alternatives exist in which output signals from detectors

46, **60** are monitored simultaneously, sequentially, or periodically. Further advantages of a system **10** that includes low and high concentration gas cells **44**, **56** are extended range, compensation for cross-sensitivity to moisture, and that the system **10** avoids, or corrects, incorrect sensing due to encountering two or more analyte fluids with overlapping optical absorption bands.

[0042] Referring now to FIG. **5**, shown in a side sectional schematic view is an example of the low concentration gas cell **44** which includes an entrance **158** (shown in dashed outline) for light to enter within the gas cell **44**. Also shown is an exit **160** (in dashed outline) spaced laterally away from the entrance **158** and that allows light to exit, which is then directed towards the photo detector **46** (FIG. **2**). In this example, the entrance **158** and exit **160** are each provided on the same axial end of the gas cell **44**. Reflectors $\mathbf{162}_{1\text{-}3}$ and $\mathbf{164}_{1\text{-}2}$ are shown inside the gas cell **44** and on opposite ends, with the reflectors $\mathbf{162}_{1\text{-}3}$ on the same end as the entrance **158** and exit **160**. Reflectors $\mathbf{162}_{1\text{-}3}$ and $\mathbf{164}_{1\text{-}2}$ along with entrance **158** and exit **160** are shown in a perspective view in FIG. **5**A, these are strategically shaped so that light entering through the entrance **158** reflects from and between reflectors $\mathbf{162}_{1\text{-}3}$ and reflectors $\mathbf{164}_{1\text{-}2}$ across the length L_{44} (FIG. **5**) multiple times to increase interaction between light and any analyte gas **71** present inside the low concentration gas cell **44**. The configuration of the gas cell **44**, which in examples has a length of about 2.5 inches, and due to the multiple reflections has a light path length of around 20 inches (0.5 m), promotes the absorption of light for the detection and identification of the analyte gases **71** present in the sample of ambient fluid **70**. Examples exist in which amounts of analyte gases **71** at about 1% on a molar basis are detected and identified and to provide a sub-ppm (0.2 ppm) sensitivity. In embodiments, the low concentration gas cell **44** is the same as or similar to what is referred to as a White cell (https://en.wikipedia.org/wiki/Multipass_spectroscopic_absorption_cells).

[0043] The present system allows for field calibration of the device without the use of samples or components exterior of the device for the detection of methane, ethane, carbon monoxide and water as the device contains within all components necessary for calibration. In a non-limiting example of use, calibration is performed with the use of a vial containing known concentrations of one or more gases, such as, methane, carbon dioxide and carbon monoxide. The system can be calibrated with three known calibration points for multiple gases. A first calibration point can be "zero" gas. This occurs with the light beam from a MEMS blackbody infrared light source passing through the high concentration chamber filled with substantially clean atmosphere to the detector and with the light beam from the test and reference sources passing through the low concentration chamber filled with substantially clean atmosphere. A second calibration point is achieved by placing the vial between the MEMS blackbody IR source and the high concentration chamber (filled with clean atmosphere) and passing the light through the vial and high concentration chamber to the detector. A third calibration point is achieved by placing the vial between the test/reference sources and the low concentration chamber (filled with clean atmosphere) and passing the light through the vial and low concentration chamber to the detector.

[0044] Referring now to FIGS. **6**A and **6**B, shown in a side elevational view is a schematic example of calibrating the sensing system **10**. Included with the sensing system **10** is a calibration system **165** with reference cells or vials **166**, **168** that each contain a gas(es) that is(are) in substantially the same concentration in each cell **166**, **168**. In this example the concentration(s) of the gas(es) is(are) known, and in an embodiment, each cell **166**, **168** includes methane, ethane, carbon monoxide, or combinations thereof, and in known concentrations. As shown, the cells **166**, **168** are each coupled on ends of arms **170**, **172** respectively that are part of a pivoting mechanism. The arms **170**, **172** join one another at a pivot point **174** about which the arms **170**, **172** and cells **166**, **168** are selectively pivoted. In an embodiment, a solenoid (not shown) is also included with the mechanism, which is connected to the mechanism at the pivot point **174** and provides a means for selectively pivoting the arms **170**, **172** and cells **166**, **168**. In the example configuration of FIG. **6**A the sensing system **10** is in a "not calibrating" mode in which the cells **166**, **168** are both located out of a path of light used for detecting low concentrations of gas, e.g., between splitter **48** (FIG. **1**) and cell **46** ("low concentration path") and also out of a path of light used for detecting high concentrations of gas, e.g., in a path of the light from light source **58** irradiating cell **56** ("high concentration path"). This is the position that the vials are in during normal operation of the device and also the position the cells **166**, **168** are in for the first calibration point described above. In order to perform the second and third calibration points described above, the solenoid partially rotates the arms **170**, **172** and the cells **166**, **168** to a position in which one of the cells **166**, **168** intersects the high concentration path and the other vial intersects the low concentration path. In examples, system **10** incorporates a five point calibration by having two cells **166**, **168** containing different concentrations of the same gases, and optionally additional or different gases at known concentrations. Examples of the five calibration points include the "zero" gas point as described above. A second calibration point where the first one of the cells **166**, **168** intersects the low concentration path; a third calibration point where the second one of the cells **166**, **168** intersects the high concentration path; a fourth calibration point where the first one of the cells **166**, **168** intersects the high concentration path; and a fifth calibration point where the second one of the cells **166**, **168** intersects the low concentration path.

[0045] Shown in an overhead view in FIG. **6**C is an example of spatial positioning of the calibration system **165** in the housing **68** of the system **10** and with respect to the source assembly **14** and gas cells **44**, **56**. The pivot point **174** is mounted onto a pivot arm **178** that is supported on a lower wall of housing **68** and pivoted about arm **178** by selective operation of solenoid **176**. A non-calibration mode is shown in FIG. **6**D, in which arms **170**, **172** are oriented about pivot arm **178** so that reference cell **166** is located oblique to cell **56** and cell **168** is located oblique to entrance **158** to cell **44**. Locating cells **166**, **168** oblique to cell **56** and entrance **158** respectively, positions cell **166** out of the path of light that travels from source **58** to cell **56** and positions cell **168** out of the path of light that travels from lens **43** to entrance **158**, which does not interfere with or affect analyte sensing operations disclosed above. An advantage of the present system **10** is the ability to be "field calibrated" at or proximate to the site where analyte testing is being done, and unlike known sensing systems that require a controlled setting, such as a laboratory or certified testing facility. An

example of a calibration mode of the system **10** is shown in an elevational view in FIG. **6**E illustrating arms **170**, **172** being pivoted from the non-calibration mode of FIG. **6**D to an orientation so that cell **166** is in the path between lens **43** and entrance **158** and cell **168** is in the path between source **58** and cell **56**. In the illustrated example, known concentrations of analyte gas(es) are in each of the reference cells **166**, **168** and are the same or substantially the same in each of the cells **166**, **168**. In a specific example, in each of the cells **166**, **168** are known quantities of methane, non-methane hydrocarbons (i.e., ethane, propane, butane, etc.), carbon monoxide, carbon dioxide, oxygen, and combinations thereof. Optionally, prior to the calibration mode cells **44**, **56** are purged and refilled with a gas having no or undetectable amounts of analytes detectable by system **10** (i.e., having an absorption band coincident with spectral bands of light generated and/or processed by system **10**). An example of a gas in cells **44**, **56** during the calibration mode is fresh air drawn into the system **10** at a location spaced away from an area where an analyte(s) is(are) expected or likely to be present. As described above, when in the calibration mode, and while light from lens **43** and/or source **58** irradiates gas in cells **166**, **168**, signals from detectors **46**, **60** provide baseline values relative to known quantities of gas in the cells **166**, **168** useful for calibrating system **10**.

[0046] In a non-limiting example of calibration, the output signal(s) from irradiating the reference cells **166**, **168** is(are) compared to an expected signal(s) or signature(s) from a library or database, and software stored in memory (not shown) in the system **10** instructs a processor to correct for any offsets that are outside of a designated tolerance. For example, the system **10** determines the gas concentration by having an internal model of the instrument, which takes the system state (gas concentrations, temperatures, etc.) and outputs expected signals. The system **10** adjusts that input state until the modelled signals match those observed. The model has a series of calibration factors which adjusts output to match a particular instrument, it is the calibration factors that are adjusted by the act of calibration. The adjustments to the calibration factors are made and applied to live software in the system **10** and stored the instrument non-volatile memory. Alternative calibration methods exist, and it is within the capabilities of one skilled in the art to calibrate system **10** based on signal outputs from detectors **46**, **58**. An advantage of using reference vials with the same gas concentration for calibrating systems having different gas concentration sensitivities, such as the systems described herein having two paths with two gas path lengths (e.g., high concentration of 20 mm and a low concentration of 470 mm) is that the different signals emitted from the different path lengths provides for better accuracy. In an example, obtaining output data from gas cells of different gas path lengths provides knowledge of operation of a detector when detecting an analyte that is in different concentrations in a sample.

[0047] In examples, system **10** includes a processor and a non-transitory computer-readable memory accessible by the processor and having executable code (including and in addition to that disclosed above) stored thereon. The executable code includes a set of instructions that causes a processor to perform operations that include controlling operation of LEDs **16**, **18**, **20**, **22** and the light source **58**, and adjusting operation of the system **10** and its components based on signals received via communication links **52**, **54**, **62**, **64**. Controller/power source **11** optionally includes a computer of any conventional type of suitable processing capacity, such as a personal computer, laptop computer, or any other suitable processing apparatus. It should thus be understood that a number of commercially available data processing systems and types of computers may be used for this purpose.

[0048] In a non-limiting example of operation, the system **10** (FIG. **1**) is manually transported by a technician or operator, to and/or within an environment where the ambient fluid **70** is to be evaluated for the presence of an analyte gas **71**. Electrical power is provided to the system **10** from an electrical source, such as a battery (not shown) coupled to or included with the system **10**. The electrical power is directed to the LEDs **16**, **18**, **20**, **22** as described above and via the leads **13** of the bus **12**. Resulting signals representing intensity of light sensed by one or more of the photo detectors **46**, **60** are transmitted to and received by the controller **11**. Data corresponding to the signals is stored in memory within the system **10**, or transmitted via hardwire or wireless to a remote location for storage. Based on an analysis of the data, such as by logics and executable code stored in the controller **11** or an associated processor, the presence of an analyte gas **71** in the ambient fluid **70** is detected, and in alternatives an amount of the analyte gas **71** is estimated.

[0049] Referring now to FIGS. **7**A-**7**C, shown in a perspective view are example embodiments of multi-gas detection and measurements tools **210**, **212**, **214**, which each include an example of the system **10** of FIG. **1**. As described in more detail below, these tools **210**, **212**, **214** each have a common interface. Tool **210** includes an outer body with an elongated portion, which in embodiments operates as a handle for an operator to hold and operate manually. Tool **210** is referred to herein as a hybrid customer service tool, tool **212** is referred to herein as a hybrid construction tool, and tool **214** is referred to as a hybrid leak survey tool. In alternatives, each of tools **210**, **212**, and **214** is employed in one or more of leak and odor investigations, pipeline construction pinpointing and barholing, for detecting methane, non-methane hydrocarbons (i.e., ethane, propane, butane, etc.), carbon monoxide, carbon dioxide, and oxygen. Examples of detection sensitivity of these tools **210**, **212**, **214** are methane at 5 ppm-100%, methane at 0.2 ppm-100%, carbon monoxide at 5 ppm-500 ppm, carbon dioxide at 0.2% to 30%, oxygen at 0.1% to 25%, and non-methane hydrocarbons at 10 ppm-5%. Examples of pipeline gas discrimination include 1% of natural gas mix and alternative, less than 500 ppm of natural gas mix. In examples, tools **210**, **212**, **214** are self-calibrating, such as the calibration method described above, for gases that include methane, ethane, carbon monoxide, carbon dioxide, and oxygen. Embodiments of tools **210**, **212**, **214** include removable memory, such as what is referred to as SD cards. Global positioning capabilities are included with the tools **210**, **212**, **214** via precision dual frequency Global Navigation Satellite System ("GNSS").

[0050] Shown in perspective view in FIG. **8** is an example of a head module **216** that is interchangeable within each of the tools **210**, **212**, **214** (FIGS. **7**A-**7**C) and that has a common user interface with the tools **210**, **212**, **214**. A screen **218** is shown on the head module **216**. Also on the tools **210**, **212**, **214** is a tactile interface **220** and the screen **218** and the tactile interface **220** optionally operate as a way

to input and/or receive output to and from the tools **210**, **212**, **214**. In embodiments, the screen **218** is configured to be a touch screen. Shown in FIGS. **9**A and **9**B is that on the screen **218** is a visual display **222**, which is changeable into either portrait or landscape orientations. Shown in FIGS. **10**A-**10**D are examples of different visual displays presented on the screen **218**. An advantage of the head module **216** is that when replaced or changed, data recorded with the tool **210**, **212**, **214** is alternatively retained within a portion of tool **210**, **212**, **214** different from the head module **216** and accessible or transferable for processing, or by a replacement head module. In examples, the head module **216** includes a processor, means for wireless communication, user interface software, and alternatively is connectable to a CANBUS protocol connection.

[0051] Add on modules (not shown) are optionally included with one or more of the tools **210**, **212**, **214**, examples of which insert into a battery compartment (not shown) provided in each of tools **210**, **212**, **214**. Modules include or connect to a battery (not shown) for powering the particular tool **210**, **212**, **214** coupled with the module. Examples of functionality of the add on modules includes the ability to analyze ambient fluid **70** (FIG. **1**) through means such as thermal conductivity, catalytic, and semiconductor, so that a greater variety of types of analyte gases are detected. The tools **210**, **212**, **214** also optionally include add on sensors (not shown) for sensing different types of gas, such as for oxygen, hydrogen, and/or hydrogen sulfide. The tools **210**, **212**, **214** are also equipped with connections and software for the addition of smart probes, e.g., haptics or quantification.

[0052] The present invention described herein, therefore, is well adapted to carry out the objectives and attain the ends and advantages mentioned, as well as others inherent therein. While one or more embodiments have been given for purposes of disclosure, numerous changes exist in the details of procedures for accomplishing the desired results. For example, the modulation scheme(s) disclosed herein are useful for any type of spectroscopy. These are intended to be encompassed within the spirit of the present invention disclosed herein and the scope of the appended claims.

What is claimed is:

1. A method of evaluating an environment comprising:

irradiating a sample volume of the environment with light at a reference wavelength;

irradiating a sample volume of the environment with light at a test wavelength, the test wavelength being a wavelength that is absorbed by an analyte gas and having an intensity that is modulated to be out of phase with an intensity of the light at the reference wavelength;

sensing an intensity of the light at the reference wavelength that is transmitted through the sample volume to define a sensed reference light intensity;

sensing an intensity of the light at the test wavelength that is transmitted through the sample volume to define a sensed test light intensity;

comparing the sensed reference light intensity with the sensed test light intensity; and

identifying the presence of the analyte gas in the environment based on the step of comparing the sensed reference light intensity with the sensed test light intensity.

2. The method of claim **1**, wherein the step of comparing the sensed reference light intensity with the sensed test light intensity comprises identifying a change over time of a difference between the sensed reference light intensity and the sensed test light intensity.

3. The method of claim **1**, wherein the analyte gas comprises a first analyte gas, the light at the test wavelength comprises a first light, and the test wavelength comprises a first test wavelength, the method further comprising, identifying a second analyte gas present in the sample volume of the environment by irradiating the sample volume of the environment with a second light that is at a second test wavelength, wherein the first light comprises light generated by a first light source and the second light comprises light generated by a second light source having the same characteristics as the first light source.

4. The method of claim **3**, further comprising forming the first light by filtering a lower portion of the bandwidth of light from the first light source, and forming the second light by filtering an upper portion of the bandwidth of light from the first light source.

5. The method of claim **4**, wherein absorption bands of the first and second analyte gases overlap.

6. The method of claim **1**, wherein the light at the test wavelength comprises a first light at the test wavelength and the test wavelength comprises a first test wavelength, the method further comprising irradiating the sample volume of the environment with a plurality of lights at a plurality of test wavelengths, each of the plurality of test wavelengths being different from the first test wavelength and being different from any of the other plurality of test wavelengths, and each of the plurality of lights having an intensity that is modulated to be out of phase with an intensity of the light at the reference wavelength.

7. The method of claim **6**, further comprising controlling irradiation of the sample volume so that over a designated period of time the sample volume is irradiated with the first light at the test wavelength or one of the plurality of lights at the plurality of test wavelengths light.

8. The method of claim **7**, wherein the sample volume is continuously irradiated with the light at the reference wavelength.

9. The method of claim **6**, wherein each of the plurality of test wavelengths being a wavelength that is absorbed by a different analyte gas.

10. The method of claim **1**, wherein the environment comprises a space selected from the group consisting of ambient fluid within a residential area, a landfill, a construction site, a gas distribution facility, a gas storage facility, an area where first responders have been summoned, an industrial area, a public area, any area, space or place where the presence and/or quantity of a designated substance is being sensed, detected, or measured, and combinations.

11. The method of claim **1**, wherein the analyte gas comprises a gas selected from the group consisting of a noxious gas, carbon monoxide, carbon dioxide, hydrocarbon gases, methane, ethane, and combinations.

12. The method of claim **1**, wherein the steps of irradiating and sensing are performed using a sensing system that comprises a controller for identifying the analyte gas and a reference vial having a substance in a known concentration, the method further comprising calibrating the sensing system by irradiating the reference cell with the reference and test lights, sensing the intensity of the test lights being

transmitted through the reference cell, and adjusting the sensed test and reference light intensities transmitted through the sample volume based on sensed intensities being transmitted through the reference cell.

13. A system for evaluating an environment comprising:

a reference light source emitting a reference light having a time varying intensity;

a test light source emitting a test light having a time varying intensity modulated to be out of phase with the reference light and having a wavelength that is within an absorption band of an analyte gas;

a space in which a sample volume of the environment is contained;

an optical system comprising, an inlet in the path of the reference light, an inlet in the path of the test light, and an exit;

an emission of light comprising reference light and test light, which projects from the exit and passes through the space and the sample volume of the environment; and

a sensor strategically disposed in a path of the emission of light and on a side of the space opposite the exit.

14. The system of claim **13**, wherein the sensor is responsive to an intensity of light, the system further comprising a controller configured to receive signals from the sensor representing light intensity and identify the presence of an analyte gas in the sample volume.

15. The system of claim **13**, wherein the optical system comprises dichroic mirrors and collimators for collimating the reference light emitted from the reference light source and the test light from the test light source onto the dichroic mirrors, and wherein the collimators are supported in place by the dichroic mirrors.

16. The system of claim **13**, wherein the test light source and test light comprise a first test light source and a first test light, the system further comprising a second test light source having the same characteristics as the first test light source, the optical system comprising a band pass filter having an inlet in the path of the first test light and second test light and an exit from which a modified first test light is emitted having a bandwidth that is in the upper half of a bandwidth of the first test light and a modified second test light is emitted having a bandwidth that is in the lower half of a bandwidth of the second test light, wherein the modified first test light is in the absorption band of a first analyte gas and the modified second test light is in the absorption band of a second analyte gas, and wherein the absorption bands of the first and second analyte gases overlap.

17. The system of claim **13**, further comprising a calibration system comprising an arm that is selectively pivotable and a reference vial containing an analyte gas of a known concentration, wherein the reference vial is coupled to the arm and selectively pivoted into the path of the emission of light.

18. The system of claim **13**, further comprising a housing covering other elements of the system, a power supply in the housing, and a handle selectively held by an operator when the system is transported to and used in remote environments.

19. The system of claim **13**, wherein the sample volume of the environment is contained in a gas cell comprising a container selected from the group consisting of a low concentration gas cell and a high concentration gas cell.

20. The system of claim **13**, wherein the test light source and test light comprise a first test light source and a first test light, the system further comprising a plurality of test light sources from which a plurality of test lights are selectively emitted, wherein the first test light and the plurality of test lights are each sequentially emitted and are modulated to be out of phase with the reference light, and wherein the reference light is continuously emitted.

* * * * *