Title: DIFFERENTIAL ABSORPTION LIDAR

Abstract: A system for remotely detecting gas concentration is provided. The system includes a plurality of light sources. At least a first one of the light sources generates light having a first wavelength and a first polarization, and at least a second one of the light sources generates light having a second, different wavelength and a second polarization that is orthogonal to the first polarization. The light from the light sources is placed on a common transmission path, and is directed to a target area by a steering mirror. Light reflected from the target area is received and directed to a detector. The detector provides information regarding the time of arrival and amplitude of the received light, allowing range and gas concentration information to be obtained. In some embodiments the detector is an imaging detector, allowing three-dimensional range information to be obtained from the target area from a single light pulse.
DIFFERENTIAL ABSORPTION LIDAR

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 62/233,768, filed September 28, 2015, the entire disclosure of which is hereby incorporated herein by reference.

FIELD

Systems and methods for remotely monitoring gas emissions are provided.

BACKGROUND

The detection of greenhouse gas emissions has become an important part of ensuring the efficient operation of various systems, and compliance with environmental regulations. For example, remote leak detection from an aircraft or spacecraft platform is essential for efficiently monitoring manufacturing zones, agricultural areas, pipeline systems, drilling operations, and the like. In addition to simple leak detection, it is desirable to provide information regarding the magnitude of a detected leak, and the precise location of the leak. Also, it is desirable to provide such information quickly and conveniently.

One way of obtaining information regarding the amount of atmospheric trace gases is to sense the spectral absorption of reflected sunlight. In particular, the amount of absorption of light at wavelengths corresponding to the spectral lines of the gas of interest can be detected and measured. In general, the higher the absorption of light at such wavelengths, the higher the concentration of the associated gas in the portion of the atmosphere from which the sampled light was collected. Similarly, the absorption of thermal emissions by atmospheric trace gases can be measured to obtain information regarding the amount of such gases. Various spectrometers have been developed for enabling such measurements. For example, Fourier transform spectrometers have been developed that are capable of high spectral resolution. However, such instruments are relatively large and complex. Other instruments for sensing light within a narrow range of wavelengths include devices utilizing optical cavities, such as Fabry-Perot interferometers and multiple cavity filters formed from thin films. However, the sensitivity and signal to noise ratio of such devices has been limited.

One approach to providing a filter having characteristics precisely correlated to the gas being sensed is to provide a cell containing a sample of the gas of interest. By
comparing the difference between the light passed through the gas-containing cell to a
detector, and light received at a detector that has not been passed through the cell,
information regarding the presence of that gas in the atmosphere can be obtained.
Although systems using samples of the gas being sensed are capable of providing filter
characteristics that are correlated to that gas, they are difficult to implement.

Another approach is to known as a Differential Absorption Lidar (DIAL). In a
DIAL system, on line and offline pulses of light are directed towards an area of interest.
The on line light has a wavelength that coincides with an absorption line of a gas of
interest. The offline wavelength is selected so that it is substantially less affected or
unaffected by the gas of interest. By comparing an intensity of light of the first
wavelength that has been reflected from the area of interest to the intensity of light of the
second wavelength that has been reflected from the area of interest, an estimated amount
of the gas of interest that the light has passed through can be determined. In previous
DIAL systems, cavity seeding and locking has been used to control laser wavelength and
linewidth. However, such systems do not achieve desired levels of laser beam combining
and energy profile matching. In addition, previous implementations of DIAL systems
have been expensive and complex to implement. Furthermore, previous DIAL systems do
not accomplish both gas sensing and 3D topographical imaging simultaneously.
Accordingly, previous implementations of these systems have required multiple passes
over the area of interest.

In some previous instruments, a 3D imaging system is used in combination with a
separate methane sensing system. As another example, a system performs data fusion
with respect to data from multiple image sensors and data from a differential absorption
LIDAR carried by an aircraft. The method of acquiring data using such a system includes
the steps of: (a) turning ON a DIAL sensor to detect a target of interest during a first flight
pass over a region of interest (ROI), wherein the target of interest is a gas or oil pipeline
leak; (b) detecting the target of interest using the DIAL sensor; and (c) storing location of
the detected target in a look up table (LUT). The method also includes the steps of: (d)
during a second flight pass over the ROI, triggering another sensor to turn ON at or about
the location stored in the LUT; and (e) confirming presence of the target of interest using
both ON-sensors. If necessary, a third flight pass over the ROI is conducted and yet
another sensor is triggered to turn ON at or about the location stored in the LUT. Presence
of the target of interest is confirmed using all three ON-sensors. Accordingly, such systems require multiple passes over an area of interest.

**SUMMARY**

Embodiments of the present disclosure provide an advanced Differential Absorption Lidar (DIAL) instrument or system for measuring gas concentration remotely. In at least some embodiments, a unique DIAL system is provided. The DIAL system operates by using pulses that are both on-line and off-line of a targeted molecular absorption feature. The DIAL system uses Volume Bragg Gratings (VBGs) for laser wavelength and linewidth control. In accordance with further embodiments of the present disclosure, the system incorporates polarization combining, polarization circularization, reference pick-off, and fiber coupling. These provisions can help ensure that the on-line and off-line beams interact with the target in like manner.

In accordance with still further embodiments of the present disclosure, the DIAL system may be configured as a flash DIAL system. The flash DIAL invention incorporates a multiple pixel sensor array. In operation, the flash DIAL system can simultaneously combine topography (3D imaging) and gas detection in an integrated single sensor. This can improve spatial resolution and chemical sensitivity at reduced size, weight, and power (SWaP) as compared to alternative systems. The flash LIDAR topographic modality uses a single pulse to illuminate a whole scene imaged onto a focal plane array. The flash LIDAR focal plane array observes a pulse waveform from each pixel, giving the capability to calculate pulse time of flight and therefore distance at each pixel. Embodiments of the present disclosure use the same waveform capture at each pixel to capture DIAL information by using pulses that are both on-line and off-line of a targeted molecular absorption feature.

**BRIEF DESCRIPTION OF THE DRAWINGS**

Fig. 1 depicts an arrangement for sensing gas emissions in accordance with embodiments of the present disclosure;

Fig. 2 depicts a sensor system in accordance with embodiments of the present disclosure;

Fig. 3 is a block diagram depicting components of a sensor system in accordance with embodiments of the present disclosure;

Fig. 4 is a schematic depiction of components of a sensor system in accordance with embodiments of the present disclosure;
**Fig. 5** is a schematic depiction of a beam coupling assembly in accordance with embodiments of the present disclosure;

**Fig. 6** is a schematic depiction of a laser monitor assembly in accordance with embodiments of the present disclosure; and

**Fig. 7** is a block diagram depicting aspects of a method for sensing gas emissions in accordance with embodiments of the present disclosure.

**DETAILED DESCRIPTION**

A remote sensor system or a light detection and ranging (LIDAR) system 104 in accordance with embodiments of the present invention, in an exemplary operating environment, is depicted in **Fig. 1**. The LIDAR system 104, also referred to herein as a sensor system 104, is mounted to a platform 108. In this example, the platform 108 is an airplane, however, other mobile or even stationary platforms 108 may be associated with the LIDAR system 104. Examples of other mobile platforms 108 include satellites, helicopters, unmanned aerial vehicles, autonomous rovers, balloons, cars, all-terrain vehicles, ships or other mobile platforms. Examples of stationary platforms 108 include radio towers, power transmission towers, observation towers, telephone poles, or other stationery supports. In general, the platform 108 is used to place the sensor system 104 in a location from which a survey area, target region, or scene 112 is observed. When the sensor system 104 is in a desired position with respect to the scene 112, it is operated to output illumination light 116 and pass the light through a target volume 106 to illuminate a target area or areas 114 within the scene 112. Reflected light 120 is returned from the target area 114 with the scene 112, and is detected by the LIDAR or sensor system 104. Information regarding the time of flight of the light is used to obtain range information between the sensor system 104 and the target area 114 within the scene 112. Information regarding the amplitude of the reflected light 120 is used to obtain information regarding the concentration of a gas of interest 122 within the target volume 106. The scene 112 can include a man made facility 124 or a natural feature under inspection or monitoring. Examples of a facility, structure, or area 124 that can be inspected or monitored using a sensor system 104 as disclosed herein include pipelines 128, wellheads 132, factories 136, agricultural zones 140, or the like.

As can be appreciated by one of skill in the art after consideration of the present disclosure, different target areas 114 comprising different elements or features within a scene 112 will reflect the illumination light 116 differently. For example, a terrain feature
comprising a forested hillside 128 may reflect the illumination light 116 less efficiently than a lake or pond 148. As a further example, an area within the scene 112 covered by snow will typically reflect the illumination light 116 more efficiently than an area that is not covered by snow. Accordingly, as discussed in greater detail elsewhere herein, the sensor system 104 may comprise a differential absorption LIDAR (DIAL) system that corrects for the reflectivity of surfaces within a target area 114.

As can also be appreciated by one of skill in the art after consideration of the present disclosure, information regarding the location at which an emission of a gas of interest to 122 is detected is important to efficiently addressing a potential leak or other unauthorized emission. Accordingly, at least some embodiments of the present disclosure can include a two-dimensional context camera. Still other embodiments of the present disclosure can additionally or alternatively include a three dimensional imaging type sensor that is used in connection with detecting the reflected light 120.

Fig. 2 depicts a sensor system 104 accordance with embodiments of the present disclosure. In general, the sensor system 104 features a shared enclosure or frame 204 that carries or encloses various components of the system 104. These components can include a plurality of light source assemblies 208, a beam coupling assembly 212, and transmit optics 216. The transmit optics 216 can include a wide-angle steering mirror 220. Alternatively or in addition, the transmit optics 216 can be mounted to a gimbal, to allow the field of view to be pointed at a target area 114. In accordance with still other embodiments of the present disclosure, the entire sensor system 104, or selected portions of the sensor system 104, can be mounted to a gimbal. The components of the system 104 can additionally include a detector 224, such as a single pixel detector or a multiple pixel array detector. The detector 224 can be associated with an imaging lens or a receive telescope 228, which can include an infrared lens 232. In accordance with at least some embodiments of the present invention, the transmit optics 216 and the receive telescope 228 can share the steering mirror 220. In such embodiments, a mirror or a beam splitter/combiner 236 can be provided to direct light between the steering mirror 220, the transmit optics 216, and the receive optics 228. The enclosure 204 can additionally house electronics 240, such as processors, driver circuits, memory, communications devices, and the like, and a context camera 244, as discussed in greater detail elsewhere herein.

Fig. 3 is a block diagram depicting components of a sensor system 104 in accordance with embodiments of the present disclosure. In this functional depiction, the
components of the sensor system 104 can generally be divided into those that are part of an optical bench 304, part of a light source and processing section 308, or associated with input/output functions 312. The optical bench 304 generally includes components that direct illumination light 116 from the light source assemblies 208 towards the target area 114, and that ensure the light 116 is provided at a desired wavelength, linewidth, and pulse duration. The light source and processing section 308 generally includes one or more light sources or lasers 314, signal processing and control components 316 provided as part of the electronics 240, and positioning, control, and power components 320. The components associated with input/output functions 312 can include, as examples and without limitation, communications transmitters and receivers, positioning system receivers, and connections to power sources.

The components included in the optical bench 304 more particularly include pulse generation 324 and radio frequency module 328 components that interact with one or more laser boxes or cavities 330 and thermoelectric controllers 332 to control the output wavelength of laser pulses as transmitted light 116. The optical bench 304 can further include components for monitoring the output of the light from a cavity 330. These monitoring components can include detectors 336, at least one of which is associated with a gas cell 340, and wavelength tuner electronics 344 that can operate to provide a feedback signal to the electronics 344. Still other components that can be included as part of the optical bench 304 include the steering mirror 220, which can be implemented as a wide-angle steering mirror, the context camera 244, the detector 224, and an imaging lens or receive telescope 228 that directs light received at the steering mirror 220 as reflected light 120 to the detector 224.

The components included in the positioning, control, and power components section 320 can more particularly include a single board computer 352 and/or a field programmable gate array 356, or other processing components as part of the processing and control components 316 of the electronics 240. The processing and control components 316 generally operate to control the production of light having desired characteristics at desired times, determining the time of flight of light signals, and determining the amplitude of received light. Other functions performed by the processing and control components 316 can include correlating signals received from a target area 114 to a geographic location, determining a concentration of a gas of interest 122 within a target volume 106, storing data generated by the sensor system 104, transmitting data,
receiving and implementing control commands, correlating three-dimensional sensor information with topographic maps, correlating three-dimensional sensor information with information from a two-dimensional context camera 244, or the like. In accordance with at least some embodiments, a dedicated steering mirror control section 360 can be provided.

As can be appreciated by one of skill in the art after consideration of the present disclosure, the steering mirror control section 360 can include processors, memory, and drivers for controlling operation of the steering mirror 220, and in particular in controlling the volume of interest 106 encompassed by the field of view of the sensor system 104. Other components that can be included in the positioning, control, and power components section 320 include a global positioning system (GPS) receiver 364. In addition, an inertial measurement unit 368 can be included.

The components associated with the input/output functions 312 can, more particularly, include data links such as a ground datalink 372 and a radio frequency datalink 376 to support the real time transmission of data. As can be appreciated by one skill in the art after consideration of the present disclosure, data links 372 or 376 can output information obtained by the sensor system 104 to a remote or separate system or user. Other input/output components can include a GPS antenna 380, and connections to one or more power supplies 384.

**Fig. 4** is a schematic depiction of components of a sensor system 104 in accordance with embodiments of the present disclosure. In particular, this view of the sensor system 104 depicts components of the light source assemblies 208 and beam forming components. As shown in the figure, the sensor system 104 can include multiple light source assemblies 208. Each light source assembly 208 can include a light source 314, such as a laser. As an example, but without limitation, the laser light source 314 can include a YAG laser. In addition, each light source assembly 208 can include a laser box or cavity 330. In accordance with embodiments of the present disclosure, the laser cavity 330 can include or be associated with a volume Bragg grating (VBG) 404 as an output coupler. As can be appreciated by one of skill in the art after consideration of the present disclosure, the VBG 404 of a laser source 208 functions to select the wavelength that is output by the laser source 208. Moreover, the operation of VBG 404 in this context is very reliable.

In accordance with embodiments of the present disclosure, the light 406a output by a first one of the light source assemblies 208a is selected to have a wavelength (a first
wavelength) that is absorbed by a gas of interest 122, while the light output by a second one of the light source assemblies 208b is selected to have a wavelength (a second wavelength) that is not significantly absorbed by the gas of interest 122. Moreover, the first wavelength can be selected to be a wavelength other than the wavelength at which maximum absorption by the gas of interest 122 is observed, to increase the amount of light within the wavelength that is reflected back to the sensor system 104 when the gas of interest 122 is present within the target volume. The second wavelength can be selected to be a wavelength that experiences similar rates of absorption as the first wavelength by known or expected constituent gases within the ambient environment encompassing the target volume 106.

In accordance with still further embodiments of the present disclosure, the first light source assembly 208a is configured to output light 406a having a first linear polarization, while the second light source assembly 208b is configured to output light 406b having a second linear polarization that is orthogonal to the first polarization. The second light source assembly 208b can include or be associated with a ½ wave plate 410 to impose the second polarization on the output light 408b. The light 406 output by the light source assemblies 208 is placed along a common transmission path 408 by a polarization beam combiner 412. A quarter wave plate 416 is located along the common transmission path 408, and functions to transform the polarization of the light 406 from the light source assemblies 208 into circularly polarized light 410. As can be appreciated by one of skill in the art after consideration of the present disclosure, by transforming the polarization of the light 406 from the light sources 208 into a circular polarization, the interaction of light from both light sources 208 with surfaces within the target area 114 will be similar.

A pickoff mirror 420 is located along the path of the circularly polarized light 410. The pickoff mirror 420 directs a portion of the light to a laser monitor assembly 600, discussed elsewhere herein. The portion of the light not redirected to the laser monitor assembly 600 by the pickoff mirror 420 passes through the beam splitter/combiner 236 to the steering mirror 220, which directs that light to the target area 114 as the transmitted beam 116. In accordance with embodiments of the present disclosure, an objective lens or lens assembly 424 can be provided between the quarter wave plate 416 and the pick off mirror 420, or between the pick off mirror 420 and the steering mirror 220.
The light 120 reflected from the target area 114 is received by the sensor system 104, and is directed by the steering mirror 220 to the mirror 236, and through the receive telescope 228, to the detector 224. The receive telescope 228 may be a reflecting telescope, including off-axis or cassegrain primary reflectors and fold mirrors, a field-stop, focusing lenses and filters, as appropriate to manage the placement of light onto the detector 224. Alternatively, the receive telescope 228 may be a refracting set of objective lenses with stops and filters as appropriate. In accordance with embodiments of the present disclosure, the detector 224 may comprise a single pixel detector. In accordance with still other embodiments of the present disclosure, the detector 224 may comprise a multiple pixel detector, such as a two-dimensional array detector, for example where the sensor system 104 incorporates a flash LIDAR sensor. The detector 224 operates to detect a time of arrival and an amplitude of received light. As an example, a detector 224 may comprise a 10 bit single pixel detector. As another example, a detector 224 may comprise a 10 bit detector with a 128 by 128, or other two dimensional array of pixels (i.e. the detector 224 may comprise an imaging detector to implement a flash LIDAR system).

The receive telescope 228 can operate to focus the received light 120 onto the detector 224.

Fig. 5 is a schematic depiction of a beam coupling assembly 500 in accordance with embodiments of the present disclosure. The beam coupling assembly 500 can be located between the light sources 208 and the steering mirror 220, and can be provided as part of or in association with the transmit optics 216. In accordance with embodiments of the present disclosure, each light source assembly 208 may include or be associated with a beam coupling assembly 500. In accordance with other embodiments of the present disclosure, the beam coupling assembly 500 can be located along a common transmission path 408 or 410, in which case the light source assemblies 208 share a common beam coupling assembly 500. The beam coupling assembly 500 generally includes a lens or lens assembly 504 that directs light from a laser source 208 onto a multimode fiber 508. A collimator 512 is located so as to receive light from the multimode fiber 508. The collimated light is then passed through a diffuser 516, and from there to the steering mirror 220. As can be appreciated by one of skill in the art after consideration of the present disclosure, this arrangement can have the advantage of reducing speckle in the transmitted light 116.
**Fig. 6** is a schematic depiction of a laser monitor assembly 600 in accordance with embodiments of the present disclosure. In accordance with embodiments of the present disclosure, the laser monitor assembly 600 includes a non-polarizing beam splitter 604. The non-polarizing beam splitter 604 can direct half of the light received from the pickoff mirror 420 along a first path 606a, and can direct the other half of the light along a second path 606b. Absorbers 608 can be included to prevent cross talk between the two paths 606a and 606b. Light directed along the first path 606a is received at a gas cell 340. In accordance with embodiments of the present disclosure, the gas cell 340 contains a sample of the gas of interest 122. Light exiting the gas cell 340 is provided to a first diffuser 616a and then to a first integrating sphere 620a. A first detector 336a is positioned to receive light exiting the first integrating sphere 620a. Light directed along the second path 606b is provided to a second diffuser 616b and a second integrating sphere 620b, and then to a second detector 336b. The configuration of a laser monitor assembly provided by embodiments of the present disclosure ensures even illumination of the detectors 336a and 336b, even in the presence of vibration, for example from a platform 108 carrying the sensor system 104. Moreover, as can be appreciated by one of skill in the art after consideration of the present disclosure, the laser monitor assembly 600 verifies the wavelengths and energy content of the light produced by the light source assemblies 208, and allows computation of the effective absorption cross section of the reference gas 340.

**Fig. 7** is a flowchart depicting aspects of the implementation and operation of a sensor system 104 in accordance with embodiments of the present disclosure. Initially, a determination is made as to whether the target area 114 is within the field of view of the sensor 104 (step 704). If not, the sensor system 104 can be moved by moving an associated platform 108, or the sensor system 104 enclosure 204 and/or the steering mirror 220 can be adjusted, to place the target area 114 within the field of view of the sensor system 104 (step 708).

Once the target area 114 is within the field of view of the sensor 104, the light source assemblies 208 are operated to generate light at the desired wavelengths and polarizations (step 712). In particular, the first light source assembly 208a is operated to generate light 406a having a first wavelength and a first polarization, where the first wavelength is significantly absorbed by a gas of interest. The second light source assembly 208b is operated to generate light 406b having a second wavelength and a second polarization, where the second wavelength is not significantly absorbed by the gas.
of interest. In accordance with embodiments of the present disclosure, a pulse of light 406a of the first wavelength is followed in quick succession by a pulse of light 406b of the second wavelength. For example, a pulse of light 406b of the second wavelength can follow a pulse of light 406a of the first wavelength by about 2 µS or less, where about means within +/- 5% of the stated value. As another example, a pulse of light 406b of the second wavelength can be spaced apart from a pulse of light 406a of the first wavelength by about 1 µS or less. This close temporal spacing of the light 406 pulses ensures that essentially the same target area 114 is illuminated, even when the sensor system 104 is mounted to a moving platform 108, such as an airplane.

A pulse of light 406 generated by a light source assembly 208 is placed along a common path 408 (step 716). In accordance with embodiments of the present disclosure, a polarizing beam splitter 412 receives light from the light source assemblies 208, and directs that light along the common path 408. By placing light from the different light source assemblies 208 onto a common path 408, elements within the optical train downstream of the polarizing beam splitter 412 can be shared and used to direct light of either wavelength to the same target area 114. At step 720, the light placed on the common path 408 is circularly polarized. In accordance with at least some embodiments of the present disclosure, light 410 from any of the light source assemblies 208 is circularly polarized in the same direction. As can be appreciated by one of skill in the art after consideration of the present disclosure, by circularly polarizing the different wavelengths of light, the interaction the light with the target area 114 will be substantially the same. At step 722, a portion of the light is picked-off and used to characterize the outgoing pulses. The remaining circularly polarized light 410 is then directed to the target area 114 as transmitted light 116 by the transmit optics 216 (step 724).

The transmitted light 116 passes through the atmosphere within the target volume 106 between the sensor system 104 and the target area 114, including any gas of interest 122 along that path. At least some of the transmitted light 116 is then reflected from a surface or surfaces within the target area 114, and is returned to the sensor system 104 as reflected light 120 (step 728). The reflected light 120 is directed by the steering mirror 220 through the receive telescope 228, which places the light 120 on the detector 224 (step 732).

The detector 224 obtains amplitude information and time of arrival information regarding the reflected light 120 (step 736). Accordingly, the detector 224 operates as a
range and amplitude sensor. Where the reflected light 120 is of the first wavelength, the amplitude of that light will be diminished or attenuated by the presence of the gas of interest 122 within the target volume 106. The amount of attenuation due to the presence of the gas of interest 122 rather than to other atmospheric constituents or effects can be determined by comparing the amplitude of the received light of the first wavelength to the amplitude of the light of the second wavelength. In particular, reflected light 120 of the second wavelength is relatively unaffected by the gas of interest 122, and therefore provides the reference amplitude. At step 740, the amplitude of received light of the first wavelength is compared to received light of the second wavelength, and the transmitted light characteristics fed from step 722 via path 723, to obtain information regarding the concentration path length of the gas of interest 122. In either case, the time of arrival of the reflected light 120 at the detector 224 provides information regarding the range of the sensor system 104 from the target area 114. At step 744, information regarding the range for the sensor system 104 to the target area 114 is determined. In particular, by monitoring the time elapsed between the transmission of a pulse of light from the sensor system 104, to the receipt of the reflection of that pulse at the detector 224, the laser and processing section 240 can determine a range of the target area 114 from the sensor system 104. At step 746, the concentration and range information are combined to determine the path-averaged concentration of the gas. In accordance with embodiments of the present disclosure, comparing an amplitude of light of the first wavelength received at the detector 224 to light of the second wavelength received at the detector 224 can be performed by the processor or single board computer 352. Similarly, monitoring the time of flight of a light pulse and calculation of a range between the sensor system 104 and the target area 114 can be performed by the processor or single board computer 352. Alternatively or in addition, some or all of these calculations can be performed by the FPGA 356.

A determination can then be made as to whether operation of the sensor system 104 is to be continued (step 748). If operation is to be continued, the process can return to step 704. Otherwise, the process can end.

Operation of a sensor system 104 in accordance with embodiments of the present disclosure can also include generating and providing output, for example in the form of concentration data regarding a gas of interest 122, information regarding the location at which the gas of interest 122 is detected, and generating and displaying an image depicting the detected emission of a gas of interest to 122 overlaid on or with respect to an image or
depiction of the scene 112. Moreover, embodiments of the present disclosure implementing a flash DIAL sensor system 104 can simultaneously combine topography (3D imaging) and gas detection in an integrated single sensor to provide improved spatial resolution and chemical sensitivity at reduced size, weight, and power (SWaP). The adaptation of flash LiDAR technology to add DIAL capability to provide 3D imaging and gas detection simultaneously, in real time, is unique to embodiments of the present disclosure.

The flash LiDAR topographic LiDAR modality uses a single pulse to illuminate a whole scene imaged onto a focal plane array. The flash LiDAR focal plane array observes a pulse waveform from each pixel, giving the capability to calculate pulse time of flight and therefore distance at each pixel. Embodiments of the present disclosure use the same waveform capture at each pixel to capture DIAL by using pulses that are separated in time and that are both on-line and off-line of a targeted spectroscopic absorption feature.

Accordingly, various embodiments of a sensor system 104 in accordance with embodiments of the present disclosure have been described. As can be appreciated by one of skill in the art after consideration of the present disclosure, further embodiments or modifications of embodiments are possible and within the scope of the disclosure. For example, and without limitation, the polarization characteristics and transmission paths of light of different wavelengths can be exchanged. As a further example, at least some aspects of the optical trains with respect to transmitted light and received light can be exchanged, for instance such that transmitted light is reflected from a mirror 236 before being directed to a steering mirror 220, while received light is directed by the steering mirror 220 to receive optics 228 without being reflected by an intervening mirror. Other variations and modifications are also possible.

The contents of this disclosure may have the following configurations:

(1) A sensor system, comprising:

a first light source assembly, wherein the first light source assembly is operable to output light at a first wavelength and a first polarization;

a second light source assembly, wherein the second light source assembly is operable to output light at a second wavelength and a second polarization, wherein the first wavelength is different than the second wavelength, and wherein the first polarization is orthogonal to the second polarization;
a polarization combiner, wherein the light output from the first light source assembly and
the light output from the second light source assembly are directed along a common path;
a quarter waveplate, wherein the quarter waveplate receives the light directed along the
common path, and wherein the quarter waveplate circularly polarizes the received light;
and
transmit optics, wherein the transmit optics receives light circularly polarized by the
quarter waveplate.

(2)
The sensor system of (1), wherein the first light source assembly includes a first laser, and
wherein the second light source assembly includes a second laser.

(3)
The sensor system of (1) or (2), wherein the first light source assembly further includes a
first volume Bragg grating (VBG), wherein the first VBG receives light from the first laser
and outputs light at the first wavelength, wherein the second light source assembly further
includes a second VBG, and wherein the second VBG receives light from the second laser
and outputs light at the second wavelength.

(4)
The sensor system of (3), wherein the light output by the first VBG has a first linear
polarization, and wherein the light output by the second VBG has a second linear
polarization.

(5)
The sensor system of (3) or (4), wherein the light output by the first VBG has a first line
width, and wherein the light output by the second VBG has a second line width.

(6)
The sensor system of any of (1) to (5), further comprising:
a pick off mirror; and
a laser monitor, wherein the pick off mirror is between the quarter waveplate and the
transmit optics, wherein the pick off mirror directs a portion of the light circularly
polarized by the quarter waveplate to the laser monitor, and wherein the laser monitor
detects a wavelength and energy content of the circularly polarized light.

(7)
The sensor system of (6), wherein the laser monitor includes:
a beam splitter, wherein the beam splitter receives light from the pick off mirror and divides the received light into first and second beams;

a gas cell, wherein the gas cell receives light included in the first beam;

a first integrating sphere, wherein the first integrating sphere receives the light included in the first beam that has passed through the gas cell;

a first detector, wherein the first detector receives light from the first integrating sphere;

a second integrating sphere, wherein the second integrating sphere receives the light included in the second beam; and

a second detector, wherein the second detector receives light from the second integrating sphere.

(8)
The sensor system of any of (1) to (7), wherein the transmit optics include a steering mirror.

(9)
The sensor system of (8), wherein the steering mirror directs the light circularly polarized by the quarter waveplate towards a target area.

(10)
The sensor system of any of (1) to (9), further comprising:

a receive telescope; and

a detector, wherein light reflected from the target area is received at the receive telescope and passed to the detector.

(11)
The sensor system of (10), wherein the detector is a single pixel detector.

(12)
The sensor system of (10), wherein the detector includes an array of pixels.

(13)
The sensor system of any of (10) to (12), further comprising a processor, wherein the processor determines a time of flight of light output from the laser and received at the detector, and wherein the processor receives a signal from the detector regarding an amplitude of the light received at the detector.

(14)
The sensor system of any of (1) to (13), wherein the transmit optics further include:

a multiple mode fiber;
a collimator; and
a diffuser, wherein the fiber receives the light circularly polarized by the quarter
waveplate, wherein the collimator receives light from the fiber, wherein the diffuser
receives light from the collimator, and wherein steering mirror receives light from the
diffuser.

(15)
A method for remotely measuring a gas concentration, comprising:
producing light having a first wavelength and a first polarization;
producing light having a second wavelength and a second polarization, wherein the second
polarization is orthogonal to the first polarization;
directing the light having a first wavelength and a first polarization and the light having a
second wavelength and a second polarization along a common path;
converting the first and second polarizations to a circular polarization; and
directing the light having a circular polarization to a target area.

(16)
The method of (15), wherein the light having a first wavelength and a first polarization is
produced at a first point in time, and wherein the light having a second wavelength and a
second polarization is produced at a second point in time.

(17)
The method of (16), wherein the first point in time is within about 1 microsecond or less
of the second point in time.

(18)
The method of any of (15) to (17), further comprising:
receiving first reflected light at a detector, wherein the first reflected light includes light
having a first wavelength;
determining a time of arrival and an amplitude of the light having a first wavelength;
receiving second reflected light at the detector, wherein the second reflected light includes
light having a second wavelength;
determining a time of arrival and an amplitude of the light having a second wavelength;
determining a range to the target area from at least one of:
a difference between a time of transmission and the time of arrival of the light having a
first wavelength; and
a difference between a time of transmission and the time of arrival of the light having a second wavelength; and
determining a concentration of a gas of interest from a difference between the amplitude of the light having a first wavelength and the light having an amplitude of a second wavelength.

(19)
The method of (18), wherein the detector is an imaging detector, and wherein the method further includes:
comparing three-dimensional image data from the detector with two-dimensional image data from a context camera;
displaying the combined image data.

(20)
A remote gas detection system, comprising:
a first light source assembly, wherein the first light source assembly is operable to output light at a first wavelength and a first polarization;
a second light source assembly, wherein the second light source assembly is operable to output light at a second wavelength and a second polarization, wherein the first wavelength is different than the second wavelength, and wherein the first polarization is orthogonal to the second polarization;
a polarization combiner, wherein the light output from the first light source assembly and the light output from the second light source assembly are directed along a common path;
a quarter waveplate, wherein the quarter waveplate receives the light directed along the common path, and wherein the quarter waveplate circularly polarizes the received light;
transmit optics, wherein the transmit optics receives light circularly polarized by the quarter waveplate, and wherein the transmit optics direct the circularly polarized light towards a target area; a range and amplitude sensor, wherein the range and amplitude sensor receives light reflected from the target area, and wherein the sensor provides a signal indicating a time at which the light reflected from the target area is received and an amplitude of that light;
an image sensor; and a processor, wherein the processor determines a range and concentration of a target gas using the range and amplitude sensor, wherein the processor combines information regarding the range and concentration of the target gas with image
information from the image sensor, and wherein the combined information is at least one of stored and displayed.

The foregoing discussion of the invention has been presented for purposes of illustration and description. Further, the description is not intended to limit the invention to the form disclosed herein. Consequently, variations and modifications commensurate with the above teachings, within the skill or knowledge of the relevant art, are within the scope of the present invention. The embodiments described herein and above are further intended to explain the best mode presently known of practicing the invention and to enable others skilled in the art to utilize the invention in such or in other embodiments and with various modifications required by the particular application or use of the invention. It is intended that the appended claims be construed to include alternative embodiments to the extent permitted by the prior art.
CLAIMS

What is claimed is:

1. A sensor system, comprising:
   a first light source assembly, wherein the first light source assembly is operable to
   output light at a first wavelength and a first polarization;
   a second light source assembly, wherein the second light source assembly is
   operable to output light at a second wavelength and a second polarization, wherein the first
   wavelength is different than the second wavelength, and wherein the first polarization is
   orthogonal to the second polarization;
   a polarization combiner, wherein the light output from the first light source
   assembly and the light output from the second light source assembly are directed along a
   common path;
   a quarter waveplate, wherein the quarter waveplate receives the light directed
   along the common path, and wherein the quarter waveplate circularly polarizes the
   received light; and
   transmit optics, wherein the transmit optics receives light circularly polarized by
   the quarter waveplate.

2. The sensor system of claim 1, wherein the first light source assembly
   includes a first laser, and wherein the second light source assembly includes a second
   laser.

3. The sensor system of claim 2, wherein the first light source assembly
   further includes a first volume Bragg grating (VBG), wherein the first VBG receives light
   from the first laser and outputs light at the first wavelength, wherein the second light
   source assembly further includes a second VBG, and wherein the second VBG receives
   light from the second laser and outputs light at the second wavelength.

4. The sensor system of claim 3, wherein the light output by the first VBG has
   a first linear polarization, and wherein the light output by the second VBG has a second
   linear polarization.

5. The sensor system of claim 4, wherein the light output by the first VBG has
   a first line width, and wherein the light output by the second VBG has a second line width.

6. The sensor system of claim 4, further comprising:
   a pick off mirror; and
a laser monitor, wherein the pick off mirror is between the quarter waveplate and the transmit optics, wherein the pick off mirror directs a portion of the light circularly polarized by the quarter waveplate to the laser monitor, and wherein the laser monitor detects a wavelength and energy content of the circularly polarized light.

7. The sensor system of claim 6, wherein the laser monitor includes:
   a beam splitter, wherein the beam splitter receives light from the pick off mirror and divides the received light into first and second beams;
   a gas cell, wherein the gas cell receives light included in the first beam;
   a first integrating sphere, wherein the first integrating sphere receives the light included in the first beam that has passed through the gas cell;
   a first detector, wherein the first detector receives light from the first integrating sphere;
   a second integrating sphere, wherein the second integrating sphere receives the light included in the second beam; and
   a second detector, wherein the second detector receives light from the second integrating sphere.

8. The sensor system of claim 1, wherein the transmit optics include a steering mirror.

9. The sensor system of claim 8, wherein the steering mirror directs the light circularly polarized by the quarter waveplate towards a target area.

10. The sensor system of claim 9, further comprising:
    a receive telescope; and
    a detector, wherein light reflected from the target area is received at the receive telescope and passed to the detector.

11. The sensor system of claim 10, wherein the detector is a single pixel detector.

12. The sensor system of claim 10, wherein the detector includes an array of pixels.

13. The sensor system of claim 10, further comprising a processor, wherein the processor determines a time of flight of light output from the laser and received at the detector, and wherein the processor receives a signal from the detector regarding an amplitude of the light received at the detector.
14. The sensor system of claim 7, wherein the transmit optics further include:
a multiple mode fiber;
a collimator; and
a diffuser, wherein the fiber receives the light circularly polarized by the quarter waveplate, wherein the collimator receives light from the fiber, wherein the diffuser receives light from the collimator, and wherein steering mirror receives light from the diffuser.

15. A method for remotely measuring a gas concentration, comprising:
producing light having a first wavelength and a first polarization;
producing light having a second wavelength and a second polarization, wherein the second polarization is orthogonal to the first polarization;
directing the light having a first wavelength and a first polarization and the light having a second wavelength and a second polarization along a common path;
converting the first and second polarizations to a circular polarization; and
directing the light having a circular polarization to a target area.

16. The method of claim 15, wherein the light having a first wavelength and a first polarization is produced at a first point in time, and wherein the light having a second wavelength and a second polarization is produced at a second point in time.

17. The method of claim 16, wherein the first point in time is within about 1 microsecond or less of the second point in time.

18. The method of claim 17, further comprising:
receiving first reflected light at a detector, wherein the first reflected light includes light having a first wavelength;
determining a time of arrival and an amplitude of the light having a first wavelength;
receiving second reflected light at the detector, wherein the second reflected light includes light having a second wavelength;
determining a time of arrival and an amplitude of the light having a second wavelength;
determining a range to the target area from at least one of:
a difference between a time of transmission and the time of arrival of the light having a first wavelength; and
a difference between a time of transmission and the time of arrival of the light having a second wavelength; and
determining a concentration of a gas of interest from a difference between the amplitude of the light having a first wavelength and the light having an amplitude of a second wavelength.

19. The method of claim 18, wherein the detector is an imaging detector, and wherein the method further includes:
combining three-dimensional image data from the detector with two-dimensional image data from a context camera;
displaying the combined image data.

20. A remote gas detection system, comprising:
a first light source assembly, wherein the first light source assembly is operable to output light at a first wavelength and a first polarization;
a second light source assembly, wherein the second light source assembly is operable to output light at a second wavelength and a second polarization, wherein the first wavelength is different than the second wavelength, and wherein the first polarization is orthogonal to the second polarization;
a polarization combiner, wherein the light output from the first light source assembly and the light output from the second light source assembly are directed along a common path;
a quarter waveplate, wherein the quarter waveplate receives the light directed along the common path, and wherein the quarter waveplate circularly polarizes the received light;
transmit optics, wherein the transmit optics receives light circularly polarized by the quarter waveplate, and wherein the transmit optics direct the circularly polarized light towards a target area;
a range and amplitude sensor, wherein the range and amplitude sensor receives light reflected from the target area, and wherein the sensor provides a signal indicating a time at which the light reflected from the target area is received and an amplitude of that light;
an image sensor; and
a processor, wherein the processor determines a range and concentration of a target gas using the range and amplitude sensor, wherein the processor combines information
regarding the range and concentration of the target gas with image information from the image sensor, and wherein the combined information is at least one of stored and displayed.
FIG. 2
FIG. 4
FIG. 5

FIG. 6
6/6

Start

Target in view?

Yes

Generate illumination light

Place light on common path

Circularly polarize light

Measure characteristics of transmitted light

Illuminate target

Receive reflected light

Direct received light to detector

Obtain time of arrival and amplitude information

Compare amplitudes to obtain concentration path length information

Determine range to target area

Compute path-averaged concentration

Continue?

No

End

FIG. 7
# INTERNATIONAL SEARCH REPORT

**International application No.**

PCT/US2016/054161

## A. CLASSIFICATION OF SUBJECT MATTER

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

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched to the extent that such documents are included in the fields searched

USPC: 250/330, 334, 339.1 1, 339.12; 356/237.1, 237.3, 437, 438 (keyword delimited)

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

Orbit, Google Patents, Google Scholar

Search terms used: differential absorption lidar, combiner, quarter wave plate, volume brag grating, mirror, monitor, beam splitter, integrating sphere, detector, receive telescope, dimensional imaging data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<td>US 5,179,422 A (PETERSON) 12 January 1993 (12.01.1993) entire document</td>
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Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:
  * "A" document defining the general state of the art which is not considered to be of particular relevance
  * "E" earlier application or patent but published on or after the international filing date
  * "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
  * "O" document referring to an oral disclosure, use, exhibition or other means
  * "P" document published prior to the international filing date but later than the priority date claimed

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Form PCT/ISA/210 (second sheet) (January 2015)