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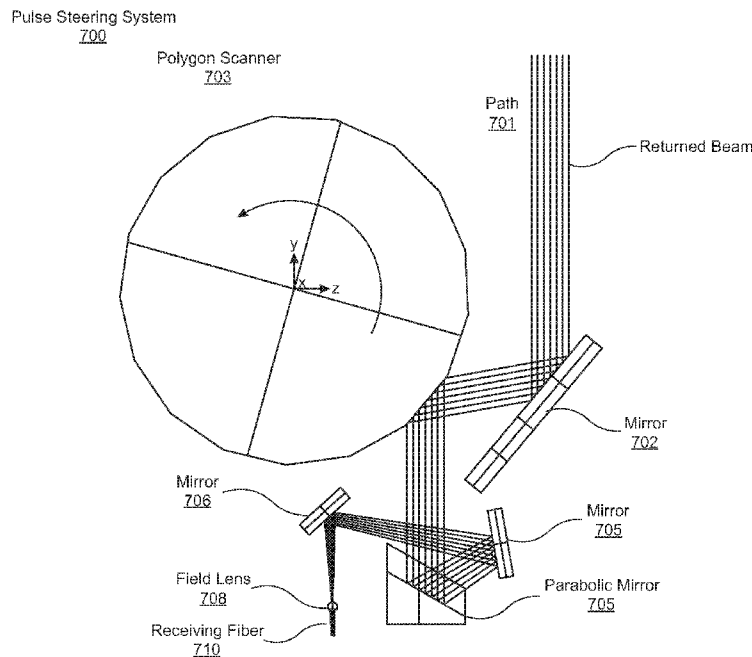


FIG. 7

(57) Abstract: In accordance with some embodiments, a light detection and ranging (LiDAR) system comprises: a light source configured to generate a pulse signal from the LiDAR system; one or more mirrors configured to steer a returned light pulse associated with the transmitted pulse signal along an optical receive path; a field lens positioned along the optical receive path, wherein the field lens is configured to redirect the returned light pulse; a fiber having a receiving end configured to receive the returned light pulse from the field lens along the optical receive path; and a light detector configured to receive the returned light pulse from an end of the fiber opposite the receiving end.



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## RECEIVE PATH FOR LIDAR SYSTEM

### CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Serial No. 62/634,084, filed February 22, 2018, entitled "Receive Path for LiDAR System," the content of which is hereby incorporated by reference for all purposes.

### FIELD

[0002] This disclosure relates generally to laser scanning and, more particularly, to using a fiber optic cable in the receive path of a laser scanning system.

### BACKGROUND

[0003] Light detection and ranging (LiDAR) systems use light pulses to create an image or point cloud of the external environment. Some typical LiDAR systems include a light source, a pulse steering system, and light detector. The light source generates light pulses that are directed by the pulse steering system in particular directions when being transmitted from the LiDAR system. When a transmitted light pulse is scattered by an object, some of the scattered light is returned to the LiDAR system as a returned pulse. The light detector detects the returned pulse. Using the time it took for the returned pulse to be detected after the light pulse was transmitted and the speed of light, the LiDAR system can determine the distance to the object along the path of the transmitted light pulse. The pulse steering system can direct light pulses along different paths to allow the LiDAR system to scan the surrounding environment and produce an image or point cloud. LiDAR systems can also use techniques other than time-of-flight and scanning to measure the surrounding environment.

### SUMMARY

[0004] The following presents a simplified summary of one or more examples to provide a basic understanding of the disclosure. This summary is not an extensive overview of all contemplated examples, and is not intended to either identify key or critical elements of all examples or

delineate the scope of any or all examples. Its purpose is to present some concepts of one or more examples in a simplified form as a prelude to the more detailed description that is presented below.

[0005] In accordance with some embodiments, a light detection and ranging (LiDAR) system comprises: a light source configured to generate a pulse signal from the LiDAR system; one or more mirrors configured to steer a returned light pulse associated with the transmitted pulse signal along an optical receive path; a fiber having a receiving end configured to receive the returned light pulse along the optical receive path; and a light detector configured to receive the returned light pulse from an end of the fiber opposite the receiving end.

[0006] In accordance with some embodiments, a light detection and ranging (LiDAR) system comprises: a light source configured to generate a pulse signal from the LiDAR system; one or more mirrors configured to steer a returned light pulse associated with the transmitted pulse signal along an optical receive path; a light detector configured to receive the returned light pulse; and a field lens positioned along the optical receive path, wherein the field lens is configured to redirect the returned light pulse from the one or more mirrors into the light detector.

[0007] In accordance with some embodiments, a light detection and ranging (LiDAR) system comprises: a light source configured to generate a pulse signal from the LiDAR system; one or more mirrors configured to steer a returned light pulse associated with the transmitted pulse signal along an optical receive path; a fiber having a receiving end configured to receive the returned light pulse along the optical receive path; and a light detector configured to receive the returned light pulse from an end of the fiber opposite the receiving end.

[0008] In accordance with some embodiments, a method comprises transmitting, using a light source, a pulse signal; steering, using one or more mirrors, a returned light pulse associated with the transmitted pulse signal along an optical receive path; redirecting, using a field lens positioned along the optical receive path, the returned light pulse; receiving, using a receiving end of a fiber, the returned light pulse from the field lens along the optical receive path; and receiving, using a light detector, the returned light pulse from an end of the fiber opposite the receiving end.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The present application can be best understood by reference to the figures described below taken in conjunction with the accompanying drawing figures, in which like parts may be referred to by like numerals.

[0010] FIG. 1 illustrates an exemplary LiDAR system using pulse signal to measure distances to points in the outside environment.

[0011] FIG. 2 illustrates the exemplary LiDAR system using pulse signal to measure distances to points in the outside environment.

[0012] FIG. 3 illustrates the exemplary LiDAR system using pulse signal to measure distances to points in the outside environment.

[0013] FIG. 4 depicts a logical block diagram of the exemplary LiDAR system.

[0014] FIG. 5 depicts a light source of the exemplary LiDAR system.

[0015] FIG. 6 depicts a light detector of the exemplary LiDAR system.

[0016] FIG. 7 depicts a steering system of the exemplary LiDAR system including a field lens and a fiber.

[0017] FIG. 8 depicts an exemplary configuration of the field lens and the fiber.

[0018] FIG. 9 depicts beam walk-off (in dashed line) that may occur in a steering system without the field lens and beam bending (in solid line) that may occur in a steering system with the field lens.

[0019] FIG. 10 illustrates the relationships between a returned optical signal and the angle change of a polygon in the exemplary steering system, with or without a field lens.

[0020] FIG. 11 depicts an exemplary optical coupling of the fiber to a photodetector of the exemplary LiDAR system.

## DETAILED DESCRIPTION

[0021] In the following description of examples, reference is made to the accompanying drawings which form a part hereof, and in which it is shown by way of illustration specific

examples that can be practiced. It is to be understood that other examples can be used and structural changes can be made without departing from the scope of the disclosed examples.

[0022] Some LiDAR systems use an open air optical path or optical path with one or more lenses to receive and optimize detection of returned pulse signals. This has a disadvantage in that the detection mechanism needs to either be close to where the returned pulse enters the system or a potentially complex system needs to be in place to redirect the returned pulse signal to the detector. In some embodiments of the present technology, an optical fiber is used to direct returned light pulses to a light detector. This way, the detector can be placed in an arbitrary location relative to the signal steering system that receives the return signal. Further, the detector can be placed fairly close to the exit end of the fiber, thus improving the integrity and amount of the detected light signals. Depending on how the returned light pulse is received by the LiDAR system, errors (e.g., walk-off error) that reduce signal strength or place more stringent tolerances on the system may be reduced. Some embodiments of the present technology use a field lens to redirect returned light pulses into an optical fiber core or directly into a light detector, thus reducing the errors due to walk-off of the pulses.

[0023] Some LiDAR systems use the time-of-flight of light signals (e.g., light pulses) to determine the distance to objects in the path of the light. For example, with respect to FIG. 1, an exemplary LiDAR system 100 includes a laser light source (e.g., a fiber laser), a steering system (e.g., a system of one or more moving mirrors), and a light detector (e.g., a photon detector with one or more optics). LiDAR system 100 transmits light pulse 102 along path 104 as determined by the steering system of LiDAR system 100. In the depicted example, light pulse 102, which is generated by the laser light source, is a short pulse of laser light. Further, the signal steering system of the LiDAR system 100 is a pulse signal steering system. However, it should be appreciated that LiDAR systems can operate by generating, transmitting, and detecting light signals that are not pulsed and/or use derive ranges to object in the surrounding environment using techniques other than time-of-flight. For example, some LiDAR systems use frequency modulated continuous waves (i.e., "FMCW"). It should be further appreciated that any of the techniques described herein with respect to time-of-flight based systems that use pulses also may be applicable to LiDAR systems that do not use one or both of these techniques.

[0024] Referring back to FIG. 1 (a time-of-flight LiDAR system that uses light pulses) when light pulse 102 reaches object 106, light pulse 102 scatters and returned light pulse 108 will be

reflected back to system 100 along path 110. The time from when transmitted light pulse 102 leaves LiDAR system 100 to when returned light pulse 108 arrives back at LiDAR system 100 can be measured (e.g., by a processor or other electronics within the LiDAR system). This time-of-flight combined with the knowledge of the speed of light can be used to determine the range/distance from LiDAR system 100 to the point on object 106 where light pulse 102 scattered.

[0025] By directing many light pulses, as depicted in FIG. 2, LiDAR system 100 scans the external environment (e.g., by directing light pulses 102, 202, 206, 210 along paths 104, 204, 208, 212, respectively). As depicted in FIG. 3, LiDAR system 100 receives returned light pulses 108, 302, 306 (which correspond to transmitted light pulses 102, 202, 210, respectively) back after objects 106 and 214 scatter the transmitted light pulses and reflect pulses back along paths 110, 304, 308, respectively. Based on the direction of the transmitted light pulses (as determined by LiDAR system 100) as well as the calculated range from LiDAR system 100 to the points on objects that scatter the light pulses (e.g., the points on objects 106 and 214), the surroundings within the detection range (e.g., the field of view between path 104 and 212, inclusively) can be precisely plotted (e.g., a point cloud or image can be created).

[0026] If a corresponding light pulse is not received for a particular transmitted light pulse, then it can be determined that there are no objects within a certain range of LiDAR system 100 (e.g., the max scanning distance of LiDAR system 100). For example, in FIG. 2, light pulse 206 will not have a corresponding returned light pulse (as depicted in FIG. 3) because it did not produce a scattering event along its transmission path 208 within the predetermined detection range. LiDAR system 100 (or an external system communication with LiDAR system 100) can interpret this as no object being along path 208 within the detection range of LiDAR system 100.

[0027] In FIG. 2, transmitted light pulses 102, 202, 206, 210 can be transmitted in any order, serially, in parallel, or based on other timings with respect to each other. Additionally, while FIG. 2 depicts a 1-dimensional array of transmitted light pulses, LiDAR system 100 optionally also directs similar arrays of transmitted light pulses along other planes so that a 2-dimensional array of light pulses is transmitted. This 2-dimensional array can be transmitted point-by-point, line-by-line, all at once, or in some other manner. The point cloud or image from a 1-dimensional array (e.g., a single horizontal line) will produce 2-dimensional information (e.g., (1) the horizontal transmission direction and (2) the range to objects). The point cloud or image

from a 2-dimensional array will have 3-dimensional information (e.g., (1) the horizontal transmission direction, (2) the vertical transmission direction, and (3) the range to objects).

**[0028]** The density of points in point cloud or image from a LiDAR system 100 is equal to the number of pulses divided by the field of view. Given that the field of view is fixed, to increase the density of points generated by one set of transmission-receiving optics, the LiDAR system should fire a pulse more frequently, in other words, a light source with a higher repetition rate is needed. However, by sending pulses more frequently the farthest distance that the LiDAR system can detect may be more limited. For example, if a returned signal from a far object is received after the system transmits the next pulse, the return signals may be detected in a different order than the order in which the corresponding signals are transmitted and get mixed up if the system cannot correctly correlate the returned signals with the transmitted signals. To illustrate, consider an exemplary LiDAR system that can transmit laser pulses with a repetition rate between 500 kHz and 1 MHz. Based on the time it takes for a pulse to return to the LiDAR system and to avoid mix-up of returned pulses from consecutive pulses in conventional LiDAR design, the farthest distance the LiDAR system can detect may be 300 meters and 150 meters for 500 kHz and 1 Mhz, respectively. The density of points of a LiDAR system with 500 kHz repetition rate is half of that with 1 MHz. Thus, this example demonstrates that, if the system cannot correctly correlate returned signals that arrive out of order, increasing the repetition rate from 500 kHz to 1 Mhz (and thus improving the density of points of the system) would significantly reduce the detection range of the system.

**[0029]** FIG. 4 depicts a logical block diagram of LiDAR system 100, which includes light source 402, signal steering system 404, pulse detector 406, and controller 408. These components are coupled together using communications paths 410, 412, 414, 416, and 418. These communications paths represent communication (bidirectional or unidirectional) among the various LiDAR system components but need not be physical components themselves. While the communications paths can be implemented by one or more electrical wires, busses, or optical fibers, the communication paths can also be wireless channels or open-air optical paths so that no physical communication medium is present. For example, in one exemplary LiDAR system, communication path 410 is one or more optical fibers, communication path 412 represents an optical path, and communication paths 414, 416, 418, and 420 are all one or more electrical wires that carry electrical signals. The communications paths can also include more than one of

the above types of communication mediums (e.g., they can include an optical fiber and an optical path or one or more optical fibers and one or more electrical wires).

[0030] LiDAR system 100 can also include other components not depicted in FIG. 4, such as power buses, power supplies, LED indicators, switches, etc. Additionally, other connections among components may be present, such as a direct connection between light source 402 and light detector 406 so that light detector 406 can accurately measure the time from when light source 402 transmits a light pulse until light detector 406 detects a returned light pulse.

[0031] FIG. 5 depicts a logical block diagram of one example of light source 402 that is based on a laser fiber, although any number of light sources with varying architecture could be used as part of the LiDAR system. Light source 402 uses seed 502 to generate initial light pulses of one or more wavelengths (e.g., 1550nm), which are provided to wavelength-division multiplexor (WDM) 504 via fiber 503. Pump 506 also provides laser power (of a different wavelength, such as 980nm) to WDM 504 via fiber 505. The output of WDM 504 is provided to pre-amplifiers 508 (which includes one or more amplifiers) which provides its output to combiner 510 via fiber 509. Combiner 510 also takes laser power from pump 512 via fiber 511 and provides pulses via fiber 513 to booster amplifier 514, which produces output light pulses on fiber 410. The outputted light pulses are then fed to steering system 404. In some variations, light source 402 can produce pulses of different amplitudes based on the fiber gain profile of the fiber used in the source. Communication path 416 couples light source 402 to controller 408 (FIG. 4) so that components of light source 402 can be controlled by or otherwise communicate with controller 408. Alternatively, light source 402 may include its own controller. Instead of controller 408 communicating directly with components of light source 402, a dedicated light source controller communicates with controller 408 and controls and/or communicates with the components of light source 402. Light source 402 also includes other components not shown, such as one or more power connectors, power supplies, and/or power lines.

[0032] Some other light sources include one or more laser diodes, short-cavity fiber lasers, solid-state lasers, and/or tunable external cavity diode lasers, configured to generate one or more light signals at various wavelengths. In some examples, light sources use amplifiers (e.g., pre-amps or booster amps) include a doped optical fiber amplifier, a solid-state bulk amplifier, and/or a semiconductor optical amplifier, configured to receive and amplify light signals.

[0033] Returning to FIG. 4, signal steering system 404 includes any number of components for steering light signals generated by light source 402. In some examples, signal steering system 404 may include one or more optical redirection elements (e.g., mirrors or lens) that steer light pulses (e.g., by rotating, vibrating, or directing) along a transmit path to scan the external environment. For example, these optical redirection elements may include MEMS mirrors, rotating polyhedron mirrors, or stationary mirrors to steer the transmitted pulse signals to different directions. Signal steering system 404 optionally also includes other optical components, such as dispersion optics (e.g., diffuser lenses, prisms, or gratings) to further expand the coverage of the transmitted signal in order to increase the LiDAR system 100's transmission area (i.e., field of view). An example signal steering system is described in U.S. Patent Application Serial No. 15/721,127 filed on September 29, 2017, entitled "2D Scanning High Precision LiDAR Using Combination of Rotating Concave Mirror and Beam Steering Devices," the content of which is incorporated by reference in its entirety herein for all purposes. In some examples, signal steering system 404 does not contain any active optical components (e.g., it does not contain any amplifiers). In some other examples, one or more of the components from light source 402, such as a booster amplifier, may be included in signal steering system 404. In some instances, signal steering system 404 can be considered a LiDAR head or LiDAR scanner.

[0034] Some implementations of signal steering systems include one or more optical redirection elements (e.g., mirrors or lens) that steers returned light signals (e.g., by rotating, vibrating, or directing) along a receive path to direct the returned light signals to the light detector. The optical redirection elements that direct light signals along the transmit and receive paths may be the same components (e.g., shared), separate components (e.g., dedicated), and/or a combination of shared and separate components. This means that in some cases the transmit and receive paths are different although they may partially overlap (or in some cases, substantially overlap).

[0035] FIG. 6 depicts a logical block diagram of one possible arrangement of components in light detector 404 of LiDAR system 100 (FIG. 4). Light detector 404 includes optics 604 (e.g., a system of one or more optical lenses) and detector 602 (e.g., a charge coupled device (CCD), a photodiode, an avalanche photodiode, a photomultiplier vacuum tube, an image sensor, etc.) that is connected to controller 408 (FIG. 4) via communication path 418. The optics 604 may include one or more photo lenses to receive, focus, and direct the returned signals. Light detector 404 can include filters to selectively pass light of certain wavelengths. Light detector

404 can also include a timing circuit that measures the time from when a pulse is transmitted to when a corresponding returned pulse is detected. This data can then be transmitted to controller 408 (FIG. 4) or to other devices via communication line 418. Light detector 404 can also receive information about when light source 402 transmitted a light pulse via communication line 418 or other communications lines that are not shown (e.g., an optical fiber from light source 402 that samples transmitted light pulses). Alternatively, light detector 404 can provide signals via communication line 418 that indicate when returned light pulses are detected. Other pulse data, such as power, pulse shape, and/or wavelength, can also be communicated.

**[0036]** Returning to FIG. 4, controller 408 contains components for the control of LiDAR system 100 and communication with external devices that use the system. For example, controller 408 optionally includes one or more processors, memories, communication interfaces, sensors, storage devices, clocks, ASICs, FPGAs, and/or other devices that control light source 402, signal steering system 404, and/or light detector 406. In some examples, controller 408 controls the power, rate, timing, and/or other properties of light signals generated by light source 402; controls the speed, transmit direction, and/or other parameters of light steering system 404; and/or controls the sensitivity and/or other parameters of light detector 406.

**[0037]** Controller 408 optionally is also configured to process data received from these components. In some examples, controller determines the time it takes from transmitting a light pulse until a corresponding returned light pulse is received; determines when a returned light pulse is not received for a transmitted light pulse; determines the transmitted direction (e.g., horizontal and/or vertical information) for a transmitted/returned light pulse; determines the estimated range in a particular direction; and/or determines any other type of data relevant to LiDAR system 100.

**[0038]** FIG. 7 depicts pulse steering system 700, which can be used to implement pulse steering system 404 discussed above. Pulse steering system 700 receives returned pulses along paths 701 and includes mirror 702, polygon scanner 703 (e.g., a reflective polygon rotating around the x-axis as shown in the figure), parabolic mirror 704 (e.g., a mirror focusing the pulse paths), mirror 705, and mirror 706. Part of pulse steering system 700 is also used to direct transmitting light pulses. For example, a fiber positioned with mirror 705, mirror 702, or in some location respective to polygon scanner 703 optionally provides light pulses that can be directed along different paths outside of the LiDAR system by pulse steering system 700.

[0039] In some embodiments, returned light pulses collected by pulse steering system 700 are redirected into an optical fiber (e.g., fiber 710), which carries the returned light pulses to a photodetector. This allows the pulse steering system to be located in an arbitrary position with respect to the light detector.

[0040] In some embodiments of the present technology, a lens or other optical element is used in the optical receive path to increase the tolerance of walk-off error of the returned pulses. For example, in FIG. 7, field lens 710 is placed in the path of return pulses traveling from mirror 706 to fiber 710. The use of a lens (e.g., a cylindrical lens) or other types of optical element mitigates beam walk-off in receiving channel.

[0041] FIG. 8 depicts field lens 708 positioned to redirect returned light pulses traveling along paths 701 into the fiber core 802, which is surrounded by fiber cladding 804. Without field lens 708 (or other optical elements in other embodiments), light pulses may hit fiber cladding 804 or miss fiber 710 altogether. In FIG. 8, field lens 708 is a cylindrical lens that can be shaped into spherical, conic, or aspherical shapes. The cylindrical field lens can be made using traditional lens fabrication process such glass polishing and grinding, precision glass molding, or precision plastic molding.

[0042] In some embodiments of the present technology, the field lens 708 is configured to redirect returned light pulses traveling along paths 710 directly to a detector (e.g., an avalanche photodiode). In these embodiments, the steering system does not include a fiber. The returned light pulses are directed via the mirrors of the steering system to reach the detector. The detector can be placed fairly close to or directly on the field lens to improve the integrity of the detected signals.

[0043] FIG. 9 depicts paths 901 of returned light pulses that are redirected by field lens 708 (or other elements). In contrast, paths 902 show that returned light pulses that are not redirected will completely miss fiber 710. These paths may be misaligned to fiber 710 (and more specifically to fiber core 802) because of various errors, process variations, environmental conditions, fabrication of the hardware such as the mirrors, and other effects that are difficult or impossible to fully account for. For example, polygon scanner 703 has a certain amount of jitter in its rotation speed, thus introducing walk-off of the pulses during normal operation of the steering system. When polygon scanner 703 transmits a pulse, the polygon continues to rotate, which means the optical receive path through the steering system is going to be slightly offset

from the optical transmit path through the steering system. The amount of offset depends in part on how much the polygon rotated between when the pulse was transmitted and the return pulse was received. The speed of rotation can be controlled only within a certain margin. The distance (and therefore time) a pulse must travel depends on the distance to an object that scatters the pulse. These two variations determine, in-part, the amount of rotation that occurs after a pulse is transmitted and when a corresponding return pulse is received. The use of field lens 708 (or other components) in the optical path allows the system to tolerate more variation in the rotation (and other sources in error) by redirecting more of the returned pulses into fiber core 802.

**[0044]** The improved walk-off characteristics of embodiments of the present technology are shown in FIG. 10. Curve 1004 shows that the window of polygon angles that provide for little to no degradation in the optical signal is about twice as large as the window provided without the field lens, as shown by curve 1002.

**[0045]** FIG. 11 shows one example of how the returned light pulses from the exit end of fiber 710 can be coupled to photodetector 604 (FIG. 6) by a plurality of lenses, which may be spherical, conic, aspherical, or ball lens. Coupling 1100 includes aspherical lens 1102, bandpass filter 1104 (which is matched to the light source frequency), and aspherical lens 1106. The narrow bandpass filter is positioned between the lens stack to suppress light whose wavelength is outside the signal wavelength band. The multi-layer bandpass film can also be deposited onto the plano surface of either the first lens 1102 or the second lens 1106. Cover window 1108 protects photodetector 604, which can detect when a returned light pulse is received. The coupling optic shown in FIG. 11 is applicable in cases where the detecting area of the photodetector is different from fiber core area, especially where the detecting area of the photodetector is smaller than the fiber core area. Small area detectors are generally desirable because of fast transient response and lower cost. In some examples, the detecting surface of the photodetector has a similar or identical diameter (e.g., 200  $\mu\text{m}$ ) as the optical fiber core. In other cases where the detecting area of the photodetector can be chosen to be larger than the fiber core area, detector can be placed or glued directly onto the end facet of the fiber.

**[0046]** Exemplary methods, non-transitory computer-readable storage media, systems, and electronic devices are set out in the following items:

1. A light detection and ranging (LiDAR) system comprising:

- a light source configured to generate a pulse signal from the LiDAR system;
- one or more mirrors configured to steer a returned light pulse associated with the transmitted pulse signal along an optical receive path;
- a field lens positioned along the optical receive path, wherein the field lens is configured to redirect the returned light pulse;
- a fiber having a receiving end configured to receive the returned light pulse from the field lens along the optical receive path; and
- a light detector configured to receive the returned light pulse from an end of the fiber opposite the receiving end.
2. The LiDAR system of item 1, wherein the field lens is configured to reduce walk-off error associated with the one or more mirrors.
  3. The LiDAR system of any of items 1-2, wherein the one or more mirrors include a polygon mirror configured to rotate.
  4. The LiDAR system of item 3, wherein the polygon mirror is also configured to direct the transmitted pulse signal from the LiDAR system.
  5. The LiDAR system of any of items 1-4, wherein the one or more mirrors include a parabolic mirror.
  6. The LiDAR system of any of items 1-5, further comprising:

one or more lenses between and the end of the fiber opposite the receiving end and the light detector.
  7. The LiDAR system of item 6 further comprising:

an optical filter between at least one of the one or more lenses and the light detector.
  8. The LiDAR system of item 7, wherein the optical filter is a bandpass filter with a pass band encompassing the frequency of the pulse signal.
  9. The LiDAR system of item 6, wherein the one or more lenses include a first aspherical lens and a second aspherical lens.

10. The LiDAR system of item 9, wherein a first multi-layer bandpass film is deposited on a plano surface of the first aspherical lens, and wherein a second multi-layer bandpass film is deposited on a plano surface of the second aspherical lens.

11. The LiDAR system of any of items 1-10, wherein the light detector is placed onto an end facet of the fiber.

12. The LiDAR system of any of items 1-11, wherein the light detector is an avalanche photodiode.

13. The LiDAR system of any of items 1-12, wherein the field lens is a part of a field lens group, wherein the field lens group is positioned along the optical receive path, and wherein the field lens group is configured to redirect the returned light pulse

14. A method, comprising:

transmitting, using a light source, a pulse signal;

steering, using one or more mirrors, a returned light pulse associated with the transmitted pulse signal along an optical receive path;

redirecting, using a field lens positioned along the optical receive path, the returned light pulse;

receiving, using a receiving end of a fiber, the returned light pulse from the field lens along the optical receive path; and

receiving, using a light detector, the returned light pulse from an end of the fiber opposite the receiving end.

15. The method of item 14, wherein the field lens is configured to reduce walk-off error associated with the one or more mirrors.

16. The method of any of items 14-15, wherein the one or more mirrors include a polygon mirror configured to rotate.

17. The method of item 16, wherein the polygon mirror is also configured to direct the transmitted pulse signal from the LiDAR system.

18. The method of any of items 14-17, wherein the one or more mirrors include a parabolic mirror.

19. The method of any of items 14-18, further comprising: positioning one or more lenses between and the end of the fiber opposite the receiving end and the light detector.

20. The method of item 19, further comprising: positioning an optical filter between at least one of the one or more lenses and the light detector.

[0047] Various exemplary embodiments are described herein. Reference is made to these examples in a non-limiting sense. They are provided to illustrate more broadly applicable aspects of the disclosed technology. Various changes may be made and equivalents may be substituted without departing from the true spirit and scope of the various embodiments. In addition, many modifications may be made to adapt a particular situation, material, composition of matter, process, process act(s) or step(s) to the objective(s), spirit or scope of the various embodiments. Further, as will be appreciated by those with skill in the art, each of the individual variations described and illustrated herein has discrete components and features which may be readily separated from or combined with the features of any of the other several embodiments without departing from the scope or spirit of the various embodiments.

## CLAIMS

1. A light detection and ranging (LiDAR) system comprising:
  - a light source configured to generate a pulse signal from the LiDAR system;
  - one or more mirrors configured to steer a returned light pulse associated with the transmitted pulse signal along an optical receive path;
  - a field lens positioned along the optical receive path, wherein the field lens is configured to redirect the returned light pulse;
  - a fiber having a receiving end configured to receive the returned light pulse from the field lens along the optical receive path; and
  - a light detector configured to receive the returned light pulse from an end of the fiber opposite the receiving end.
2. The LiDAR system of claim 1, wherein the field lens is configured to reduce walk-off error associated with the one or more mirrors.
3. The LiDAR system of any of claims 1-2, wherein the one or more mirrors include a polygon mirror configured to rotate.
4. The LiDAR system of claim 3, wherein the polygon mirror is also configured to direct the transmitted pulse signal from the LiDAR system.
5. The LiDAR system of any of claims 1-4, wherein the one or more mirrors include a parabolic mirror.
6. The LiDAR system of any of claims 1-5, further comprising:
  - one or more lenses between and the end of the fiber opposite the receiving end and the light detector.
7. The LiDAR system of claim 6 further comprising:
  - an optical filter between at least one of the one or more lenses and the light detector.
8. The LiDAR system of claim 7, wherein the optical filter is a bandpass filter with a pass band encompassing the frequency of the pulse signal.

9. The LiDAR system of claim 6, wherein the one or more lenses include a first aspherical lens and a second aspherical lens.

10. The LiDAR system of claim 9, wherein a first multi-layer bandpass film is deposited on a plano surface of the first aspherical lens, and wherein a second multi-layer bandpass film is deposited on a plano surface of the second aspherical lens.

11. The LiDAR system of any of claims 1-10, wherein the light detector is placed onto an end facet of the fiber.

12. The LiDAR system of any of claims 1-11, wherein the light detector is an avalanche photodiode.

13. The LiDAR system of any of claims 1-12, wherein the field lens is a part of a field lens group, wherein the field lens group is positioned along the optical receive path, and wherein the field lens group is configured to redirect the returned light pulse

14. A method, comprising:

transmitting, using a light source, a pulse signal;

steering, using one or more mirrors, a returned light pulse associated with the transmitted pulse signal along an optical receive path;

redirecting, using a field lens positioned along the optical receive path, the returned light pulse;

receiving, using a receiving end of a fiber, the returned light pulse from the field lens along the optical receive path; and

receiving, using a light detector, the returned light pulse from an end of the fiber opposite the receiving end.

15. The method of claim 14, wherein the field lens is configured to reduce walk-off error associated with the one or more mirrors.

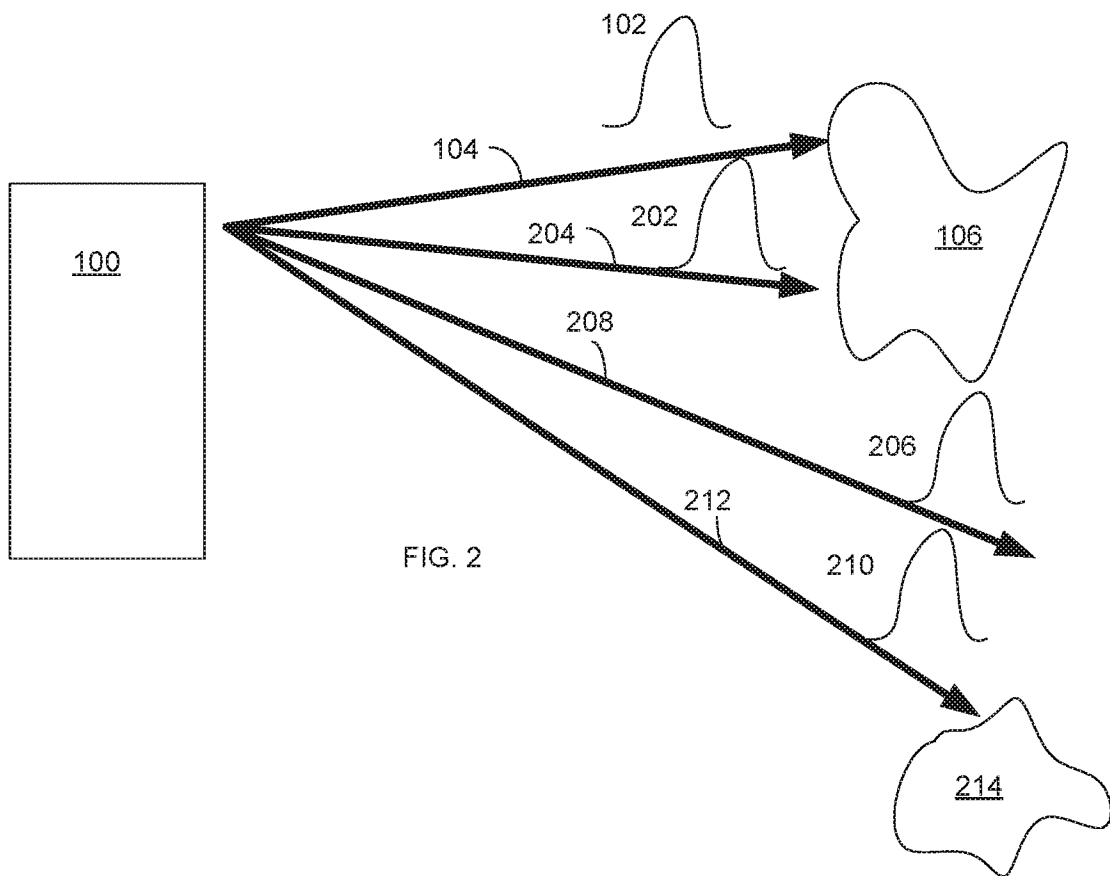
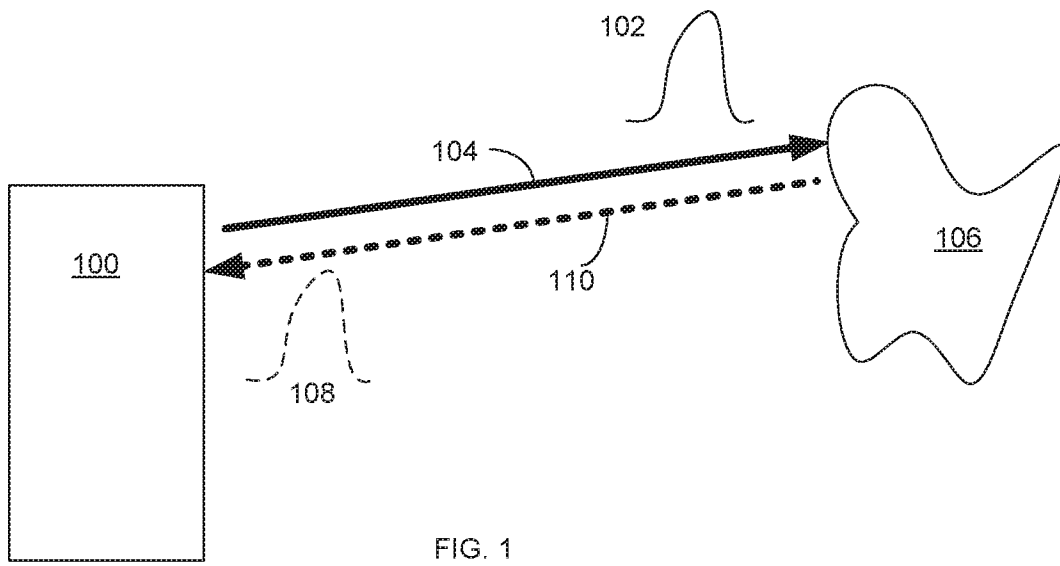
16. The method of any of claims 14-15, wherein the one or more mirrors include a polygon mirror configured to rotate.

17. The method of claim 16, wherein the polygon mirror is also configured to direct the transmitted pulse signal from the LiDAR system.

18. The method of any of claims 14-17, wherein the one or more mirrors include a parabolic mirror.

19. The method of any of claims 14-18, further comprising: positioning one or more lenses between and the end of the fiber opposite the receiving end and the light detector.

20. The method of claim 19, further comprising: positioning an optical filter between at least one of the one or more lenses and the light detector.



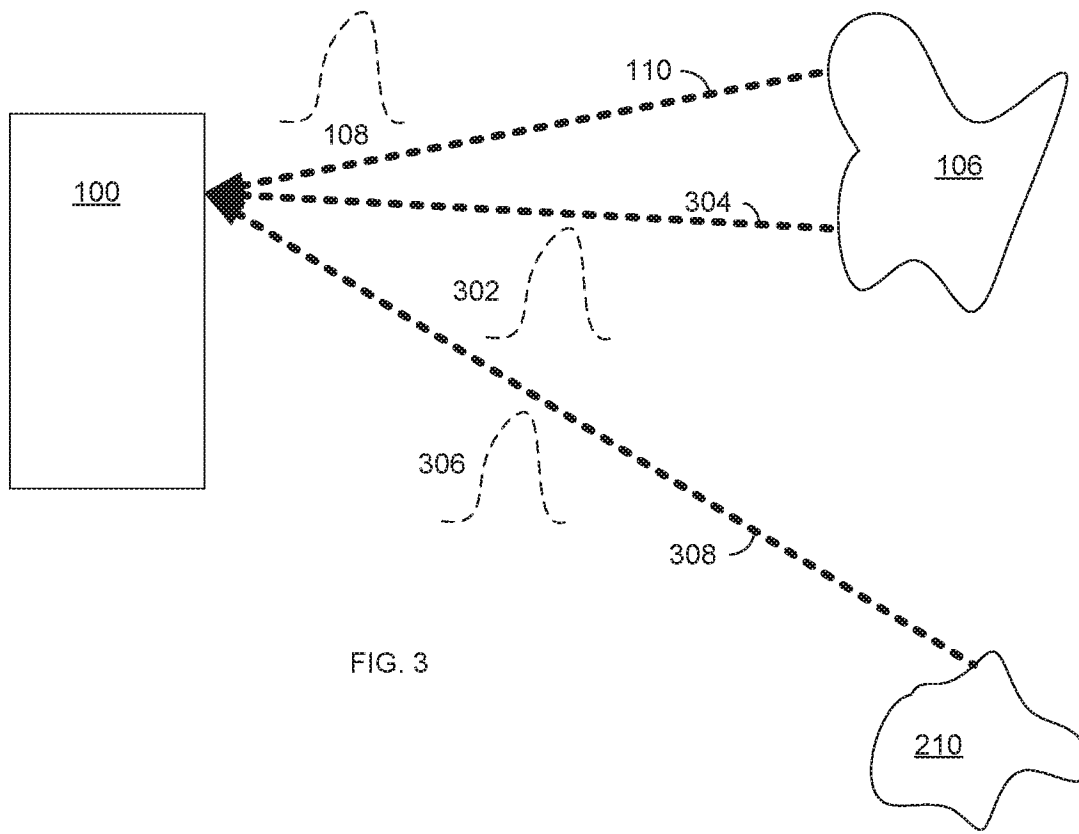


FIG. 3

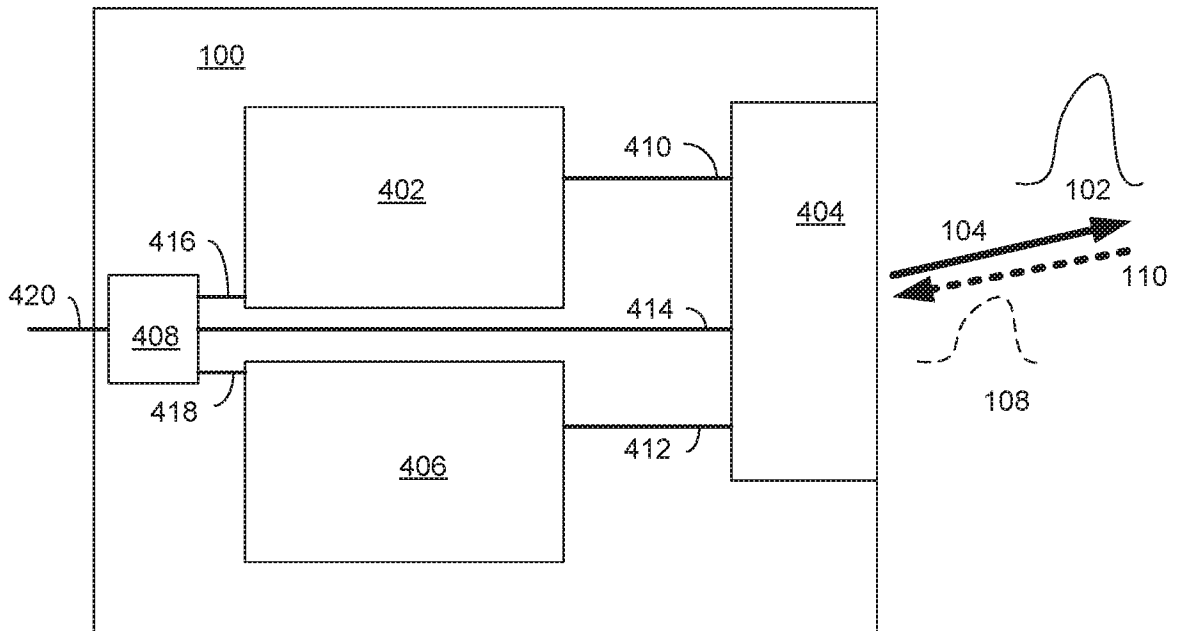


FIG. 4

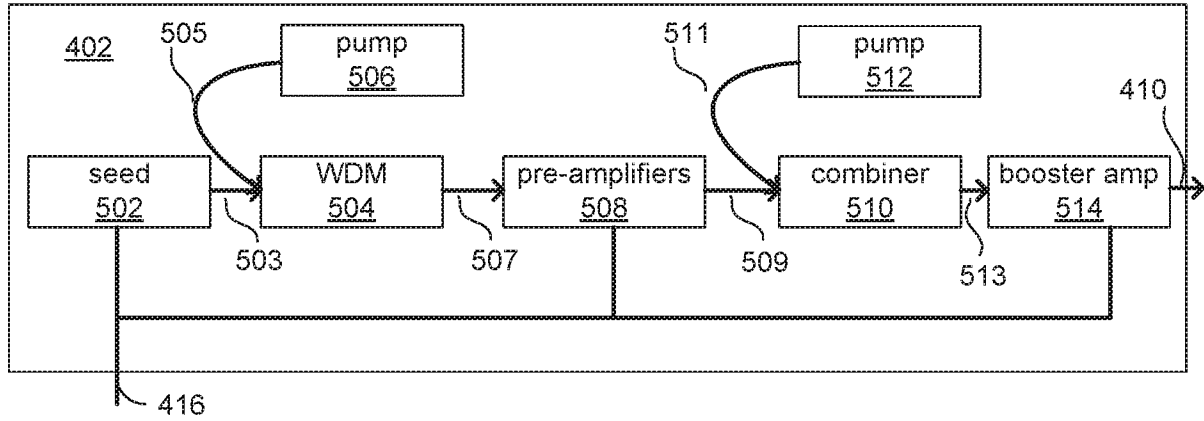


FIG. 5

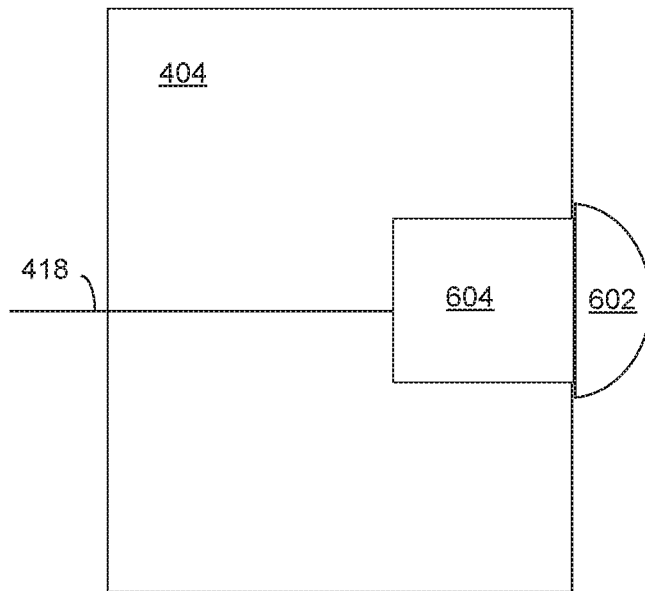


FIG. 6

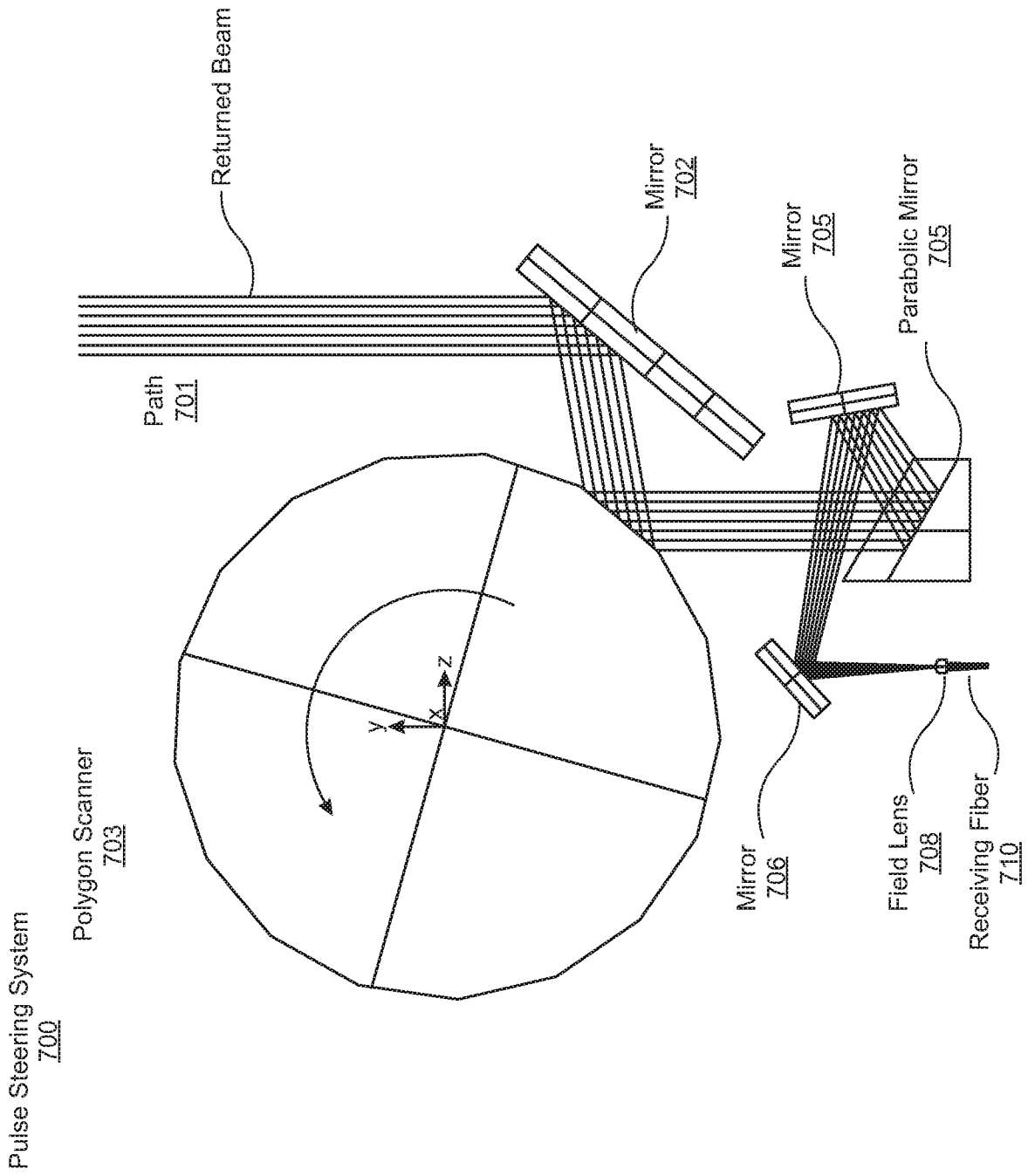


FIG. 7

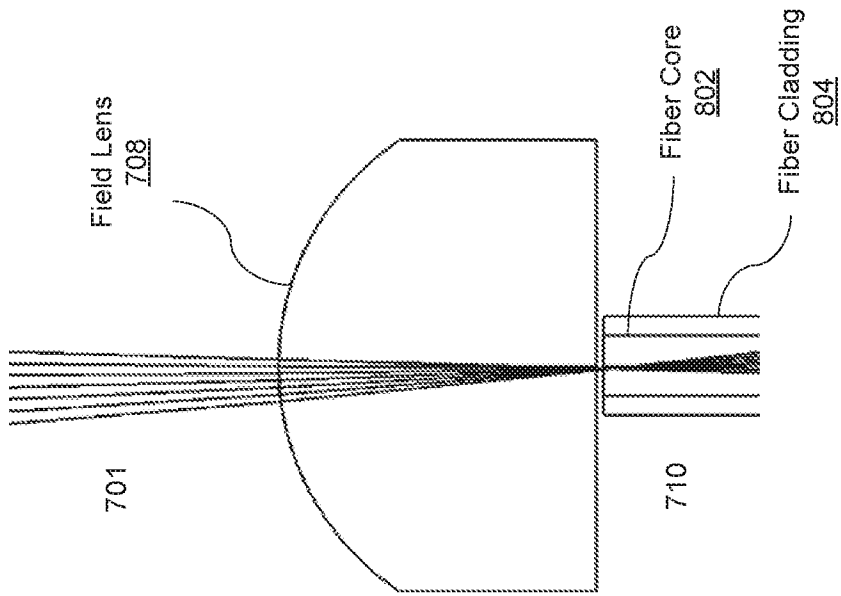


FIG. 8

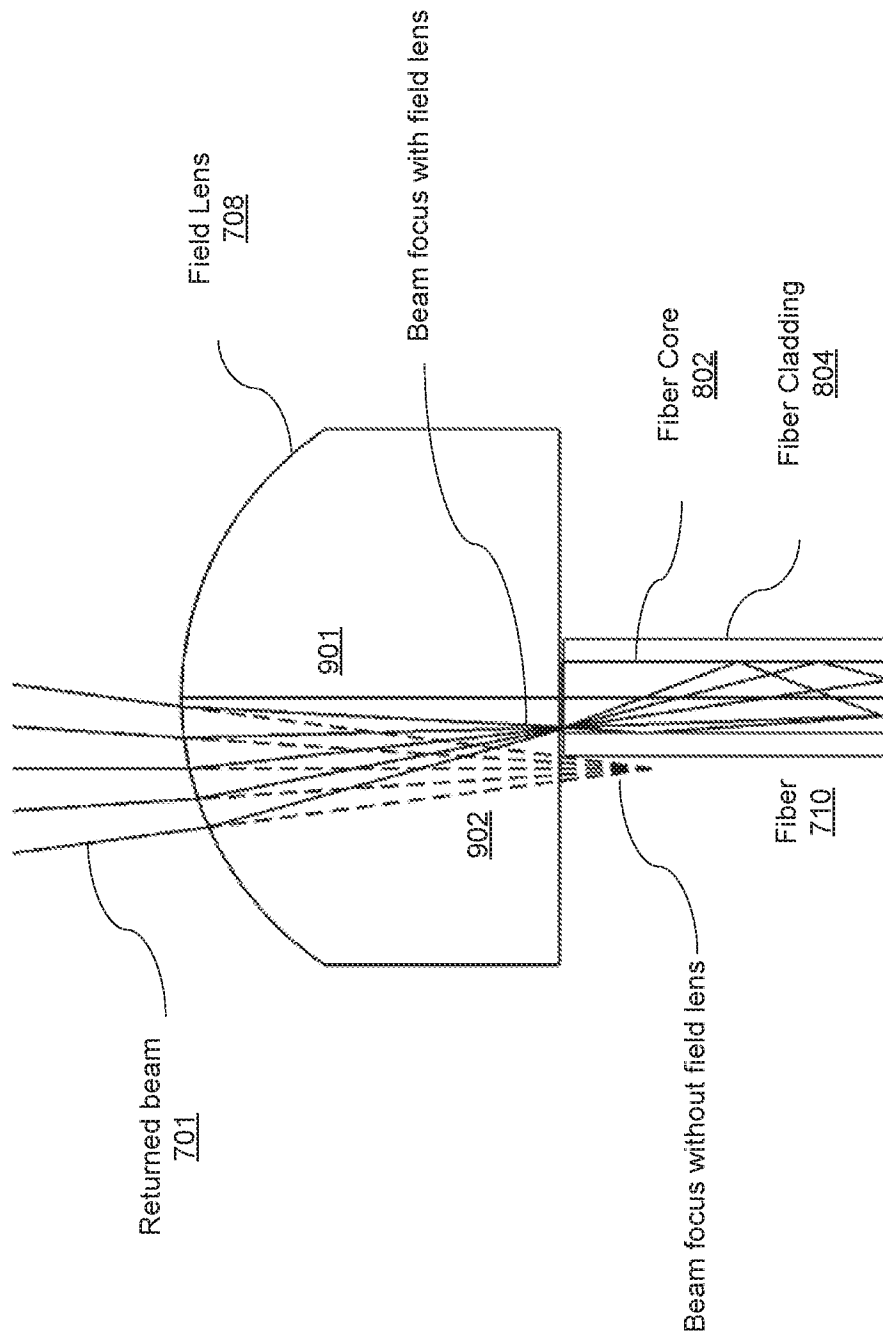


FIG. 9

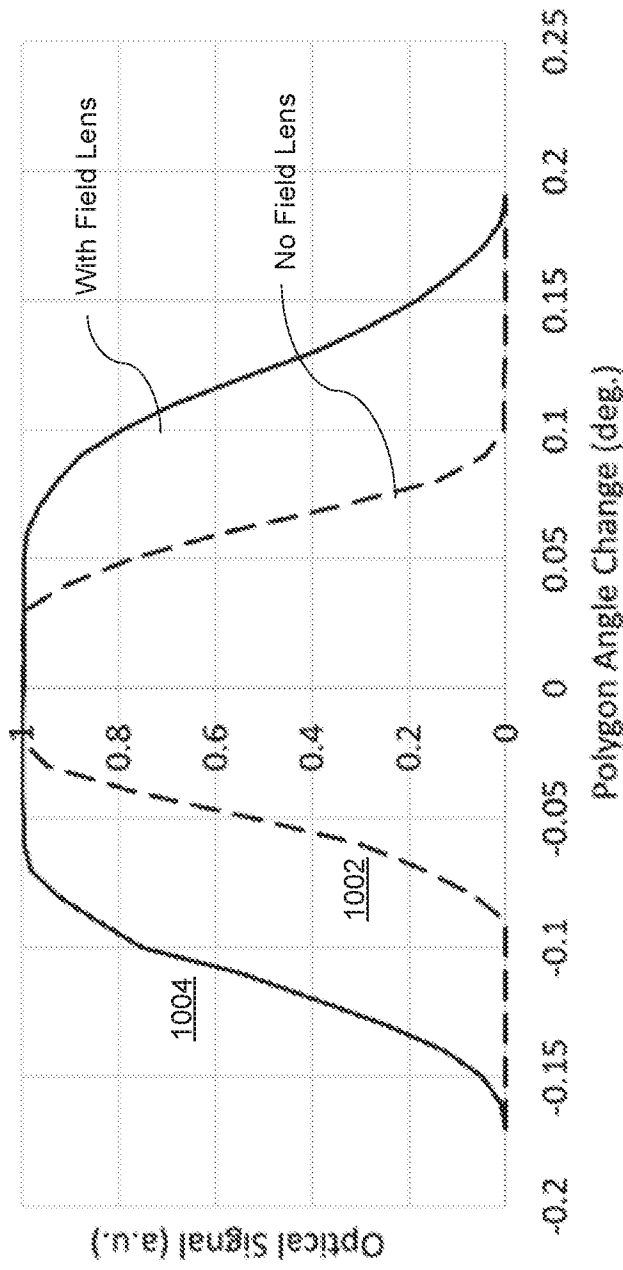


FIG. 10

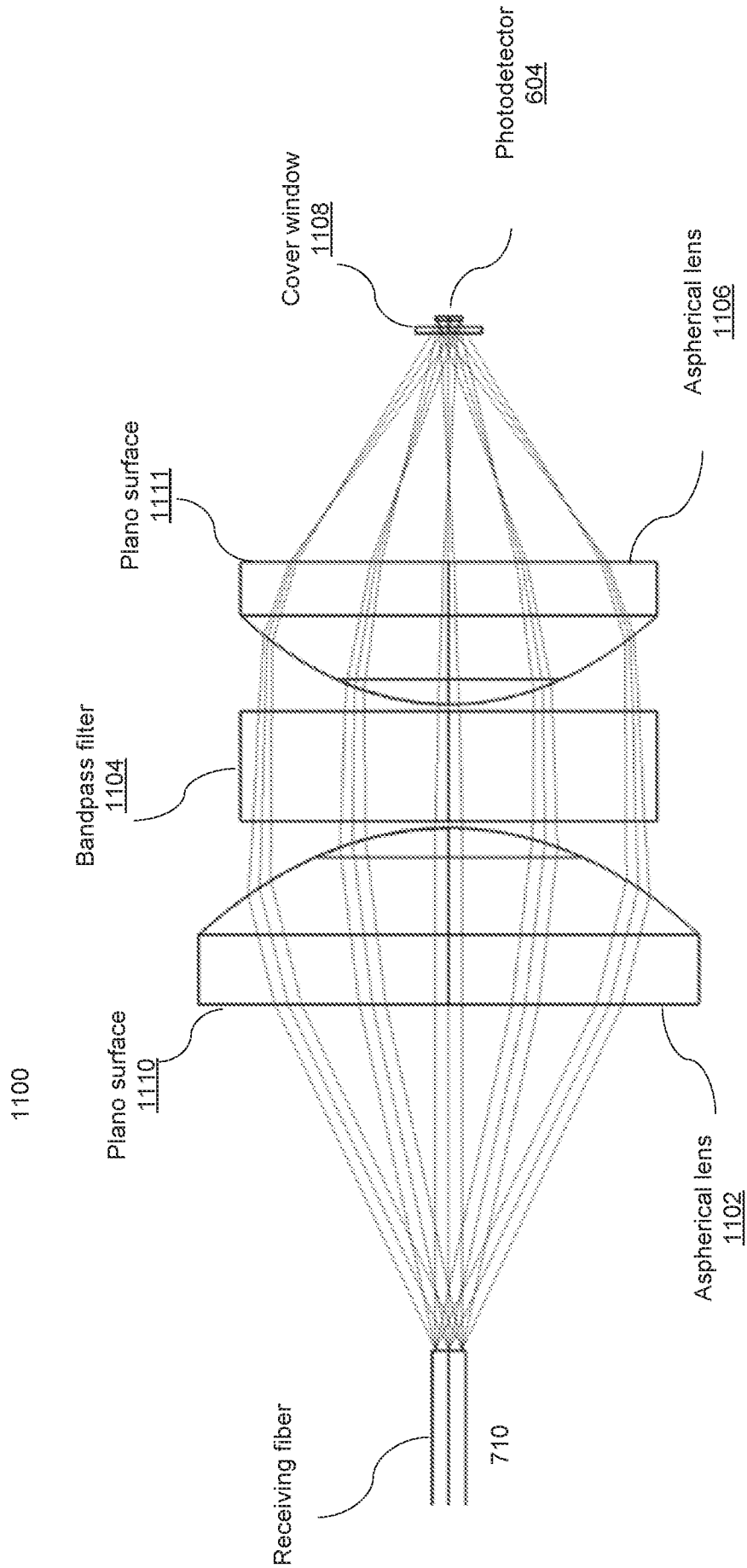


FIG. 11

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US19/19264

## A. CLASSIFICATION OF SUBJECT MATTER

IPC - G01S 7/48, 7/481, 7/486, 17/02, 17/06, 17/88, 17/89, 17/93; G02B 26/10, 26/12 (2019.01)

CPC - G01S 7/4811, 7/4812, 7/4816, 7/4817, 7/4818, 7/486, 17/003, 17/10, 17/42, 17/88, 17/936; G02B 19/0028, 19/0076, 26/12, 26/124, 26/125

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)

See Search History document

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

See Search History document

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

See Search History document

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/0078514 A1 (ZHU, X) 20 March 2014; abstract; figure 11; paragraphs [0055, 0094, 0099, 0102, 00150-00154]	1-4 & 14-17
A	US 2015/0116692 A1 (MICHIGAN AEROSPACE CORPORATION) 30 April 2015; entire document	1-4 & 14-17
A	US 2012/0221142 A1 (DOAK, A) 30 August 2012; entire document	1-4 & 14-17
A	US 5,006,721 A (CAMERON, E et al.) 09 April 1991; entire document	1-4 & 14-17
P, X	US 2018/0188355 A1 (INNOVUSION IRELAND LIMITED) 05 July 2018; entire document	1-4 & 14-17

 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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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

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

Date of the actual completion of the international search

12 April 2019 (12.04.2019)

Date of mailing of the international search report

06 MAY 2019

Name and mailing address of the ISA/

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents

P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Shane Thomas

PCT Helpdesk: 571-272-4300  
PCT OSP: 571-272-7774

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US19/19264

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1.  Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2.  Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
3.  Claims Nos.: 5-13 & 18-20  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

1.  As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2.  As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3.  As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
  
4.  No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

**Remark on Protest**

- The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- No protest accompanied the payment of additional search fees.