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(54) **THIN PROFILE WINDSHIELD MOUNTED LIDAR SYSTEM**

(71) Applicant: **Seyond, Inc.**, Sunnyvale, CA (US)

(72) Inventors: **Yufeng Li**, Milpitas, CA (US); **Haosen Wang**, Sunnyvale, CA (US); **Yimin Li**, Cuprtino, CA (US); **Junwei Bao**, Los Altos, CA (US)

(73) Assignee: **Seyond, Inc.**, Sunnyvale, CA (US)

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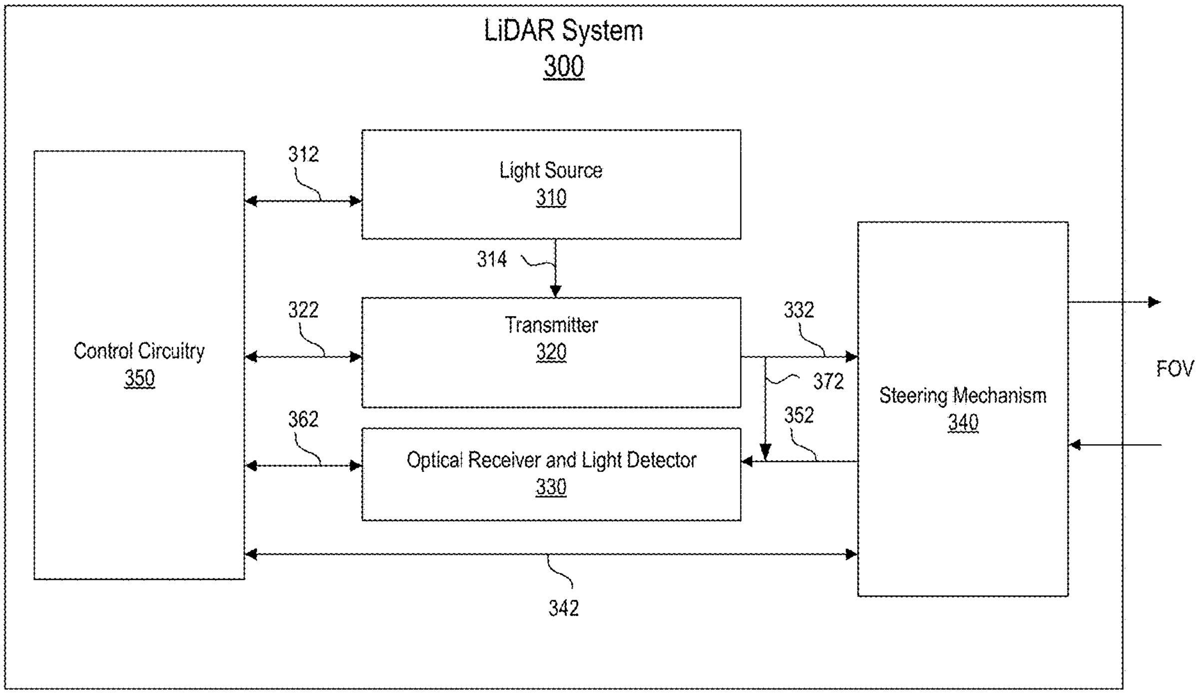
(57) **ABSTRACT**

A system for light ranging and detection (LiDAR) is disclosed herein. The system comprises a laser transmitter transmitting one or more channels of light pulses. A rotating polygon mirror having a plurality of reflective facets directs the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the system toward an external field of view and receives reflected light from the external field of view illuminated by the one or more channels of light pulses. A receiver detects the reflected light from channels corresponding to the one or more channels of light pulses. The laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface.



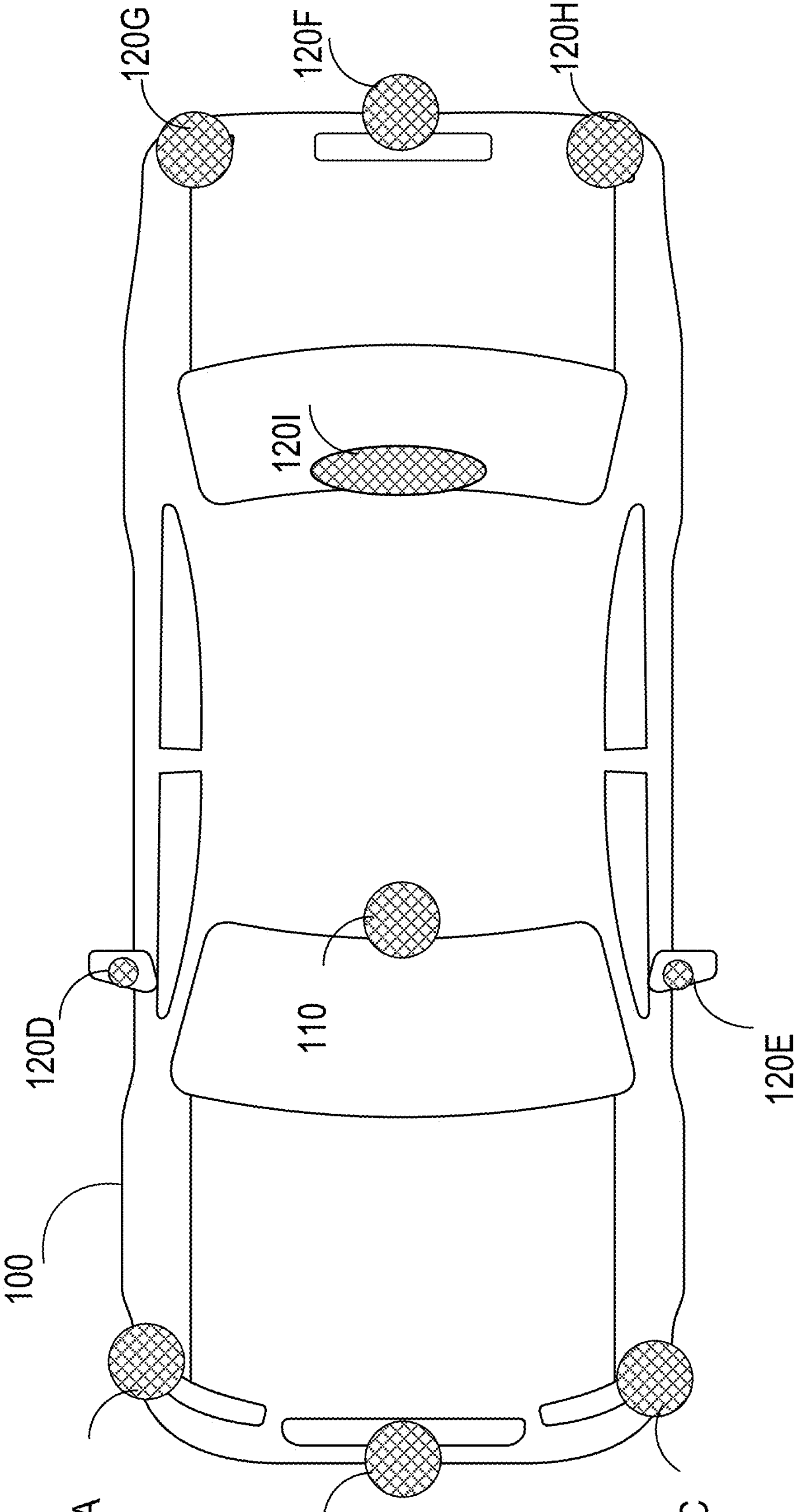


FIG. 1

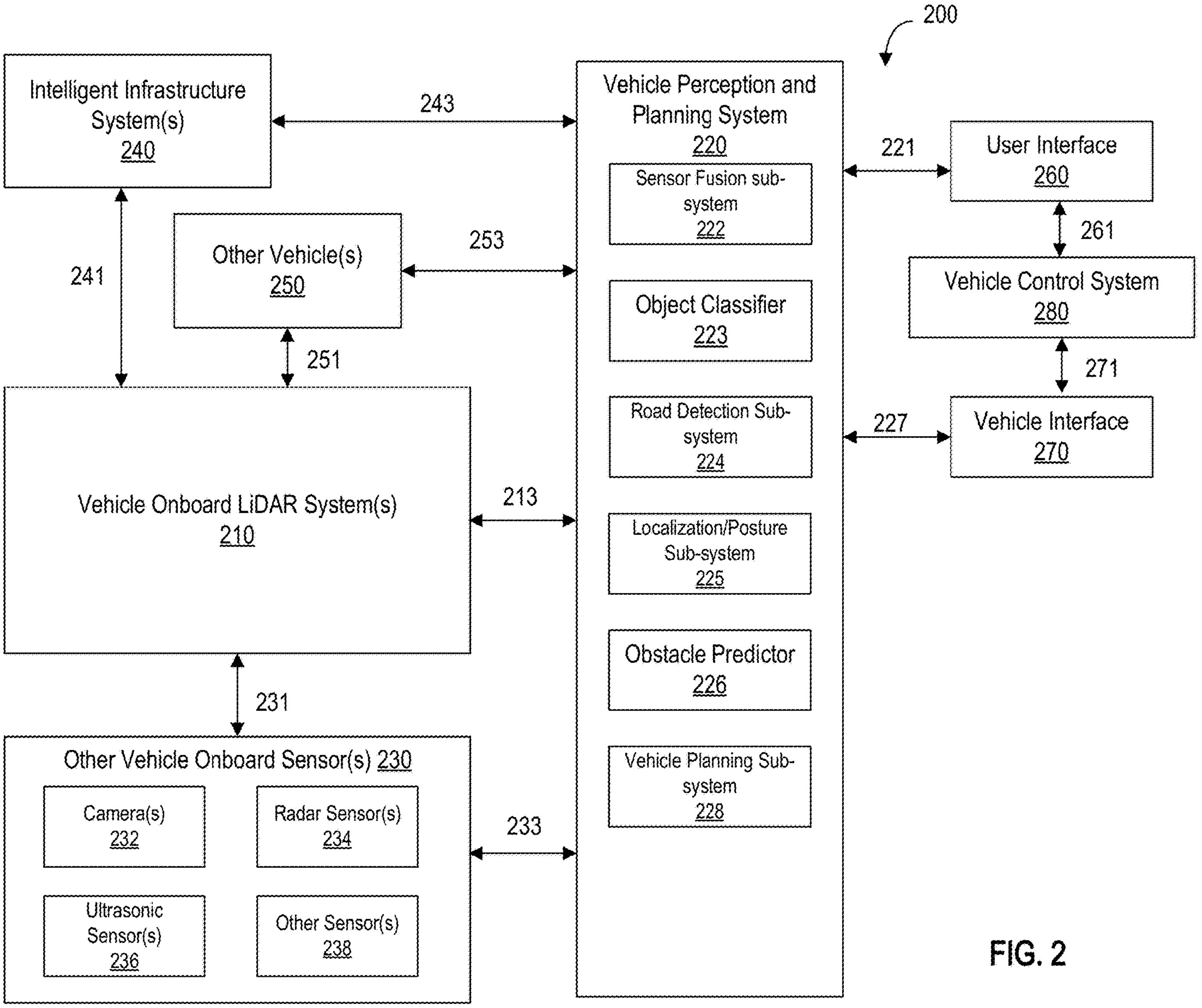

200
Intelligent Infrastructure System(s) 240
243
Vehicle Perception and Planning System 220
Sensor Fusion sub-system 222
Object Classifier 223
Road Detection Sub-system 224
Localization/Posture Sub-system 225
Obstacle Predictor 226
Vehicle Planning Sub-system 228
221
User Interface 260
261
Vehicle Control System 280
271
227
Vehicle Interface 270
241
Other Vehicle(s) 250
253
251
Vehicle Onboard LiDAR System(s) 210
213
231
Other Vehicle Onboard Sensor(s) 230
Camera(s) 232
Radar Sensor(s) 234
Ultrasonic Sensor(s) 236
Other Sensor(s) 238
233

FIG. 2

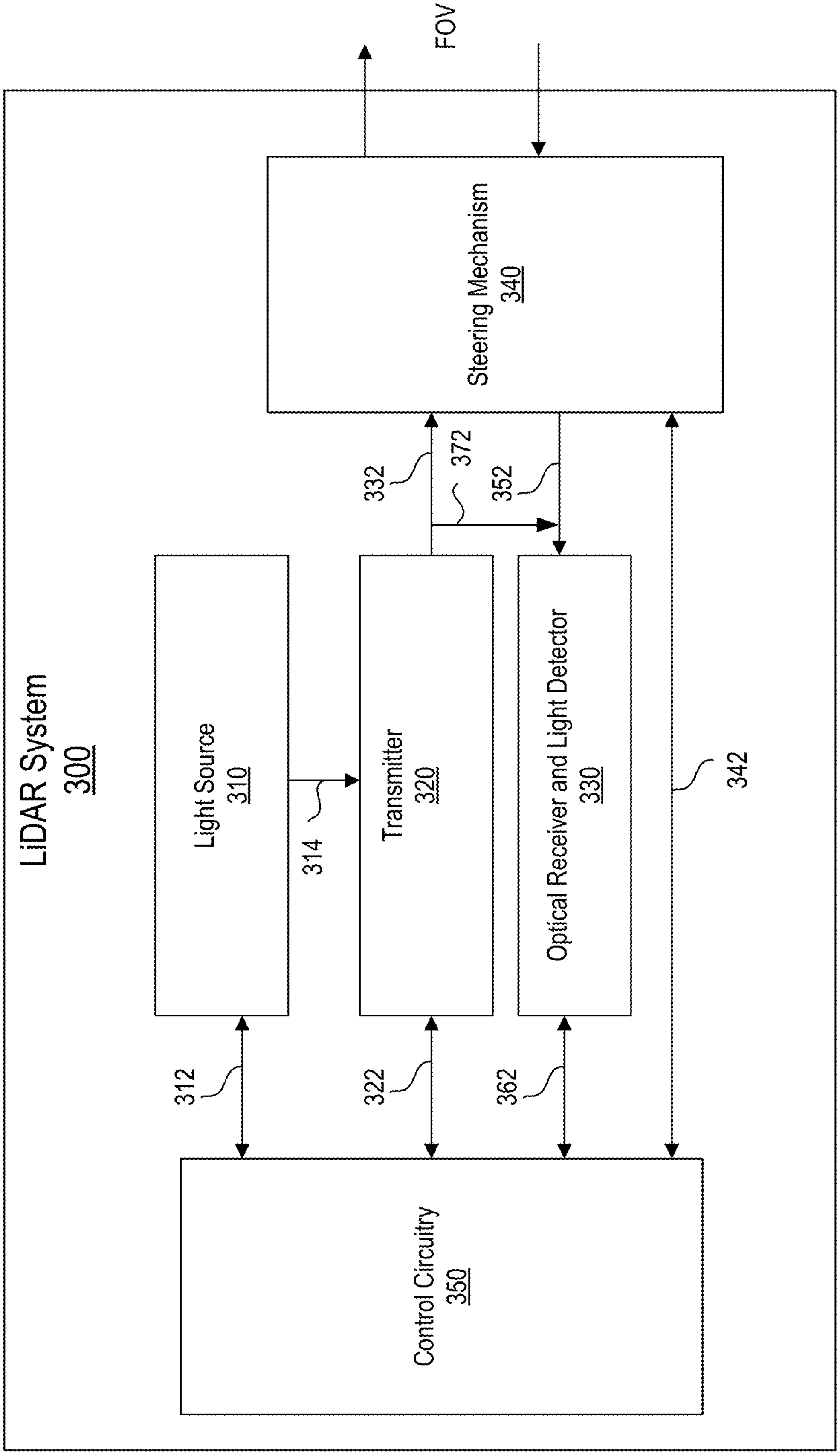

FOV
LiDAR System
300
Light Source
310
Transmitter
320
Optical Receiver and Light Detector
330
Steering Mechanism
340
Control Circuitry
350
312
314
322
332
342
352
362
372

FIG. 3

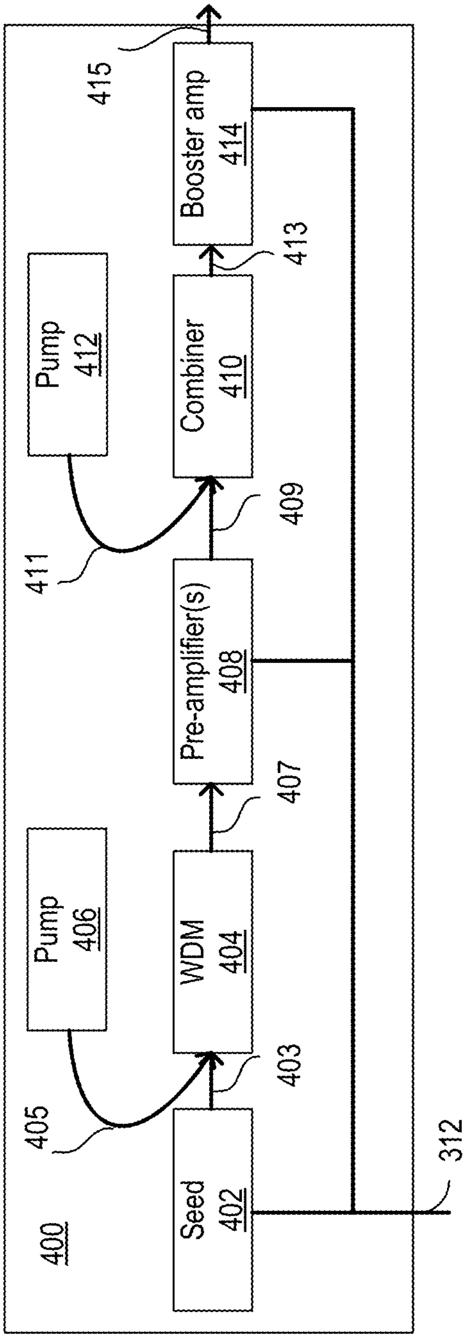

400
Seed 402
WDM 404
Pump 406
Pre-amplifier(s) 408
Combiner 410
Pump 412
Booster amp 414
403
405
407
409
411
413
415
312

FIG. 4A

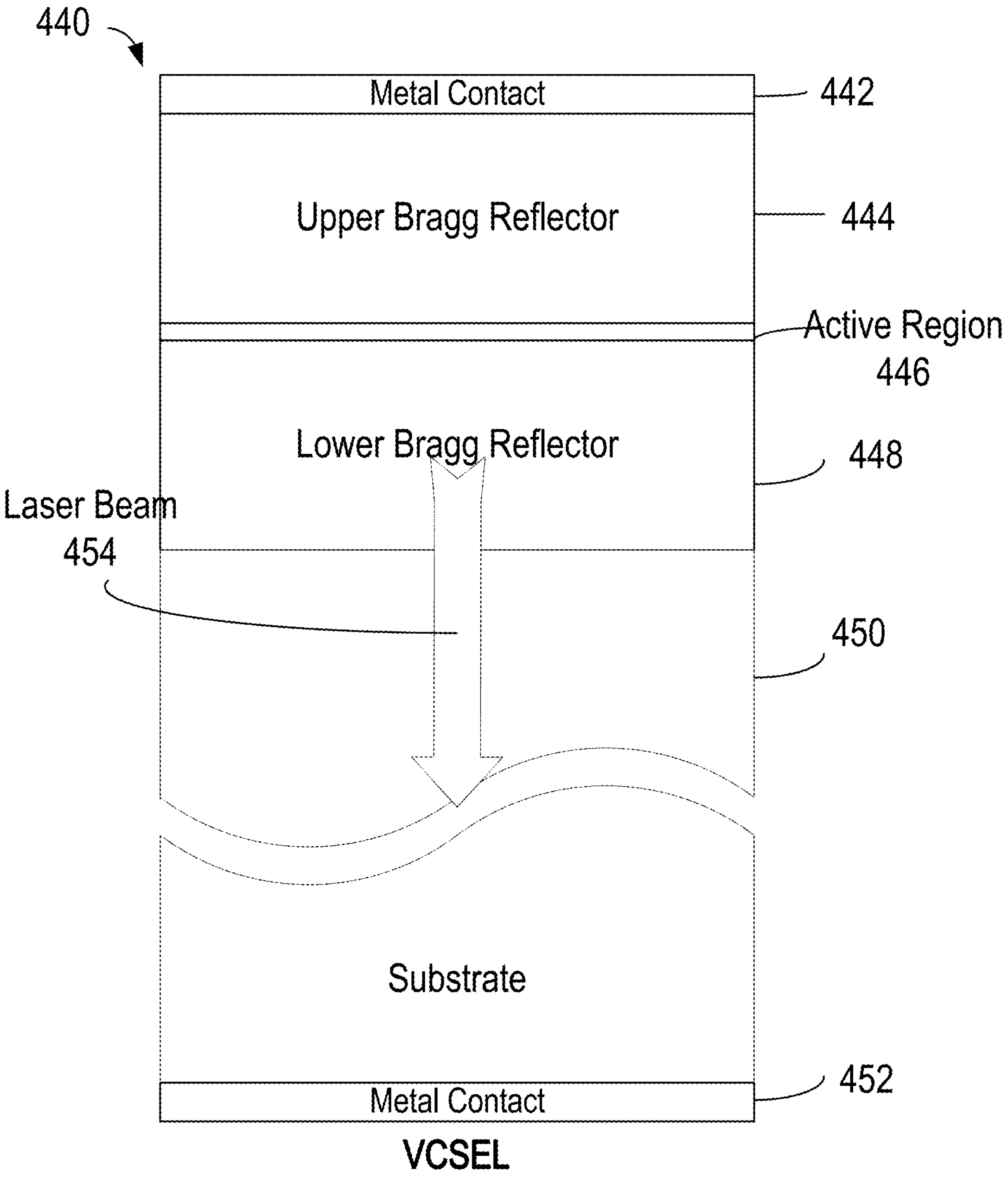

440
Metal Contact
442
Upper Bragg Reflector
444
Active Region
446
Lower Bragg Reflector
448
Laser Beam
454
450
Substrate
Metal Contact
452
VCSEL

FIG. 4B

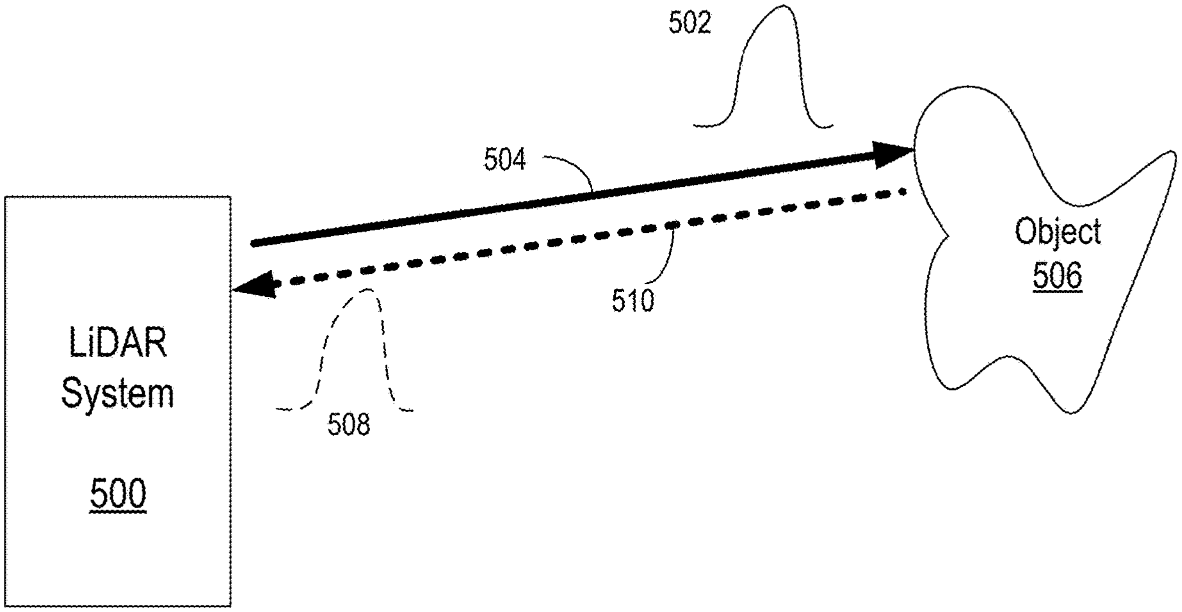


FIG. 5A

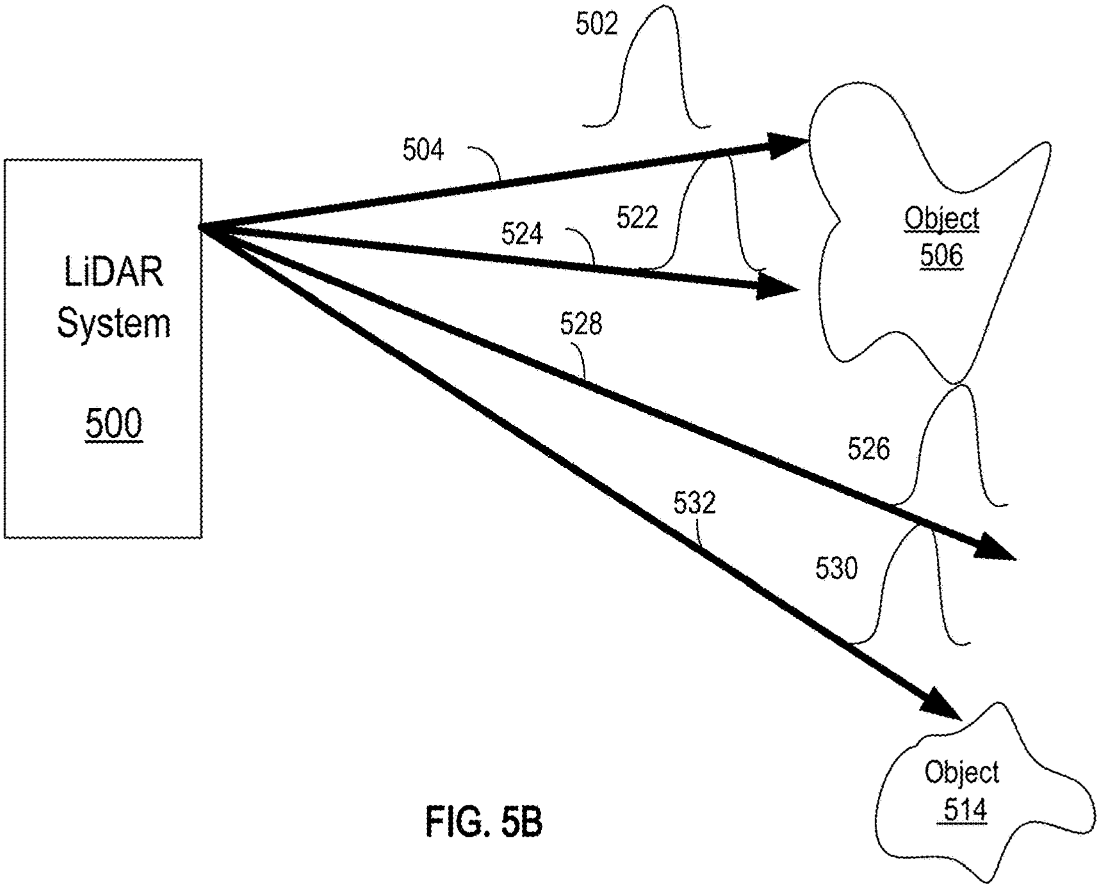

502
504
522
524
528
526
532
530
LiDAR System
500
Object
506
Object
514

FIG. 5B

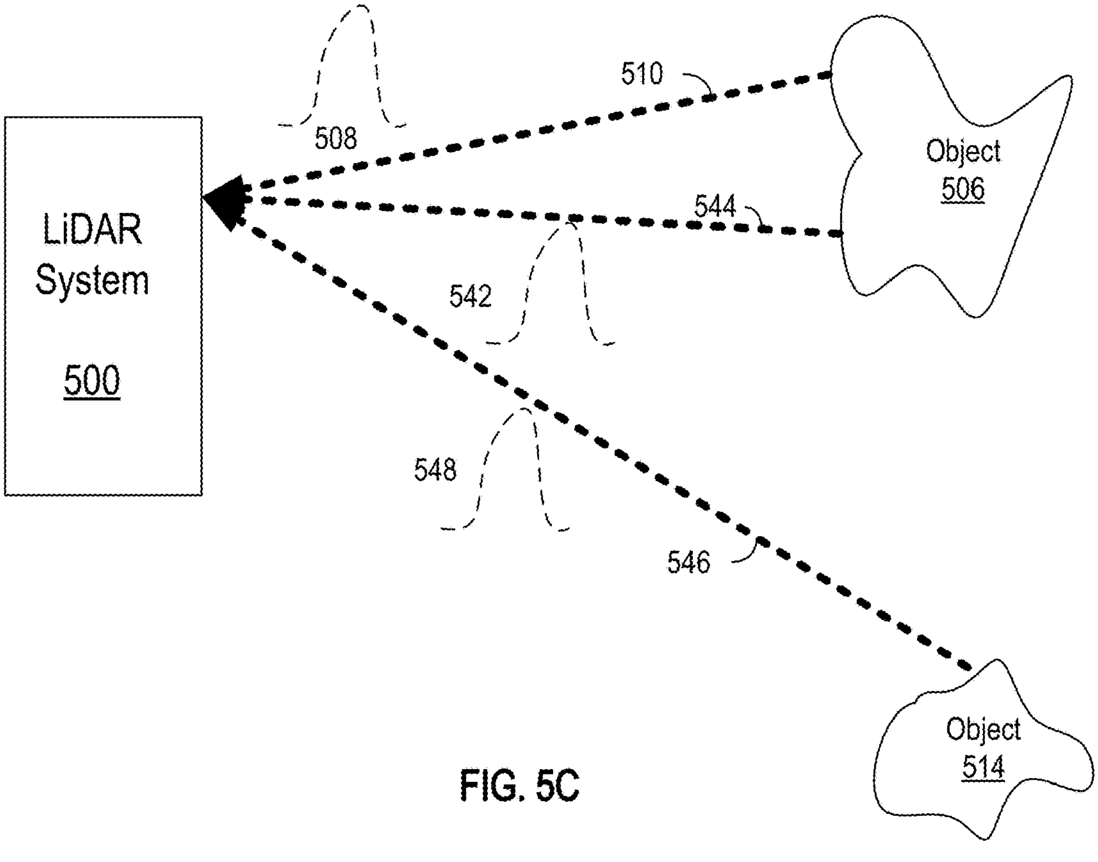

510
508
544
542
548
546
LiDAR System
500
Object
506
Object
514

FIG. 5C

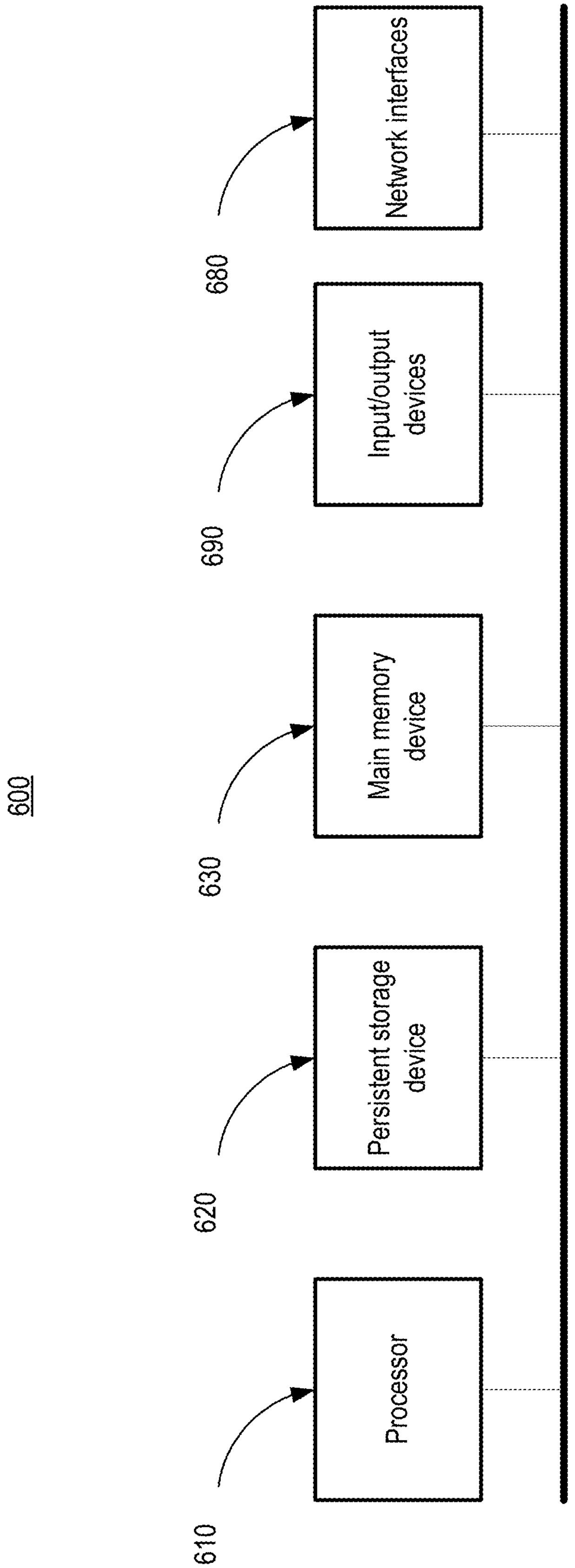

600
610
Processor
620
Persistent storage device
630
Main memory device
690
Input/output devices
680
Network interfaces

FIG. 6

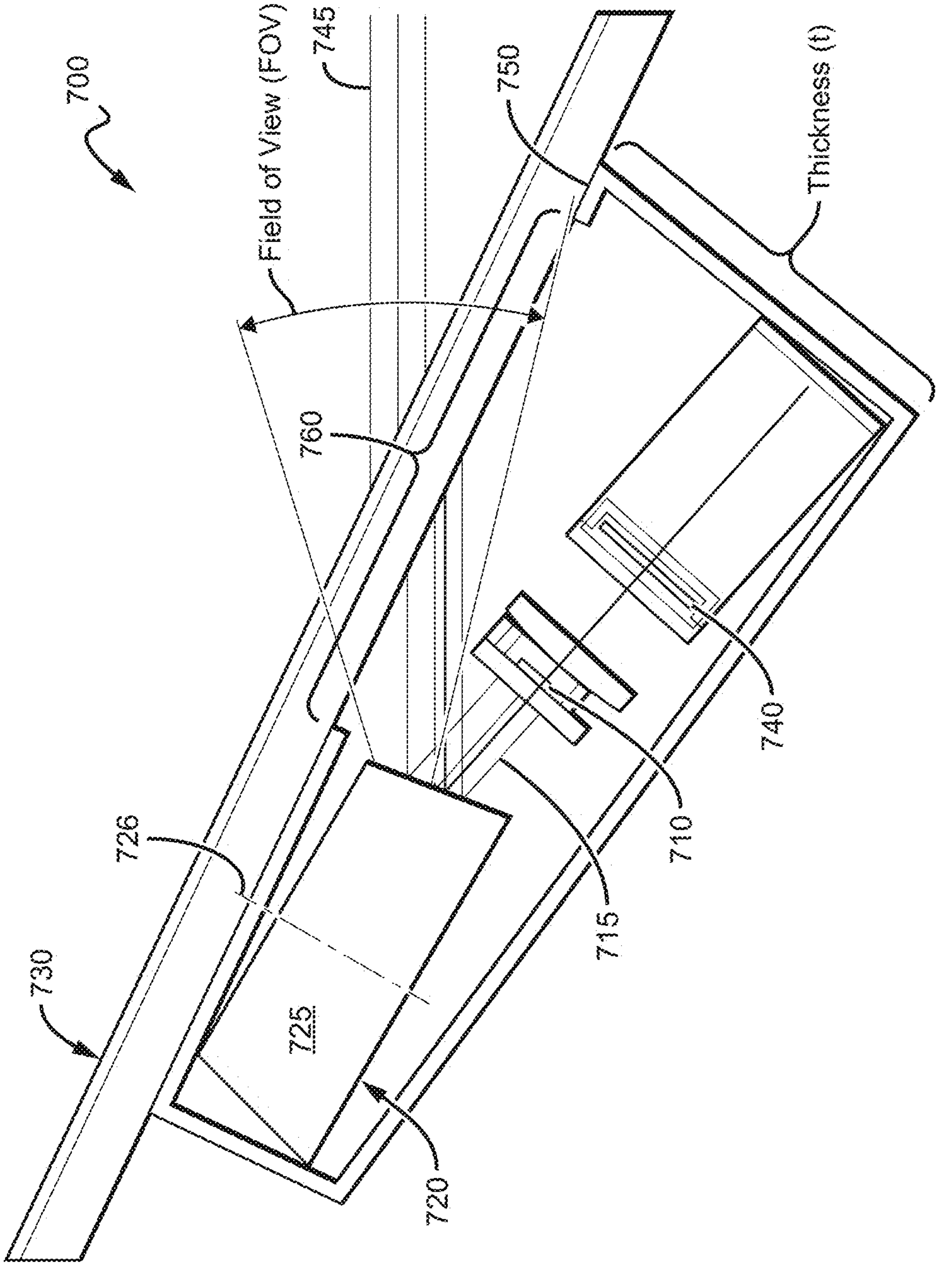

700
Field of View (FOV)
745
750
Thickness (t)
760
740
710
715
726
730
725
720

FIG. 7

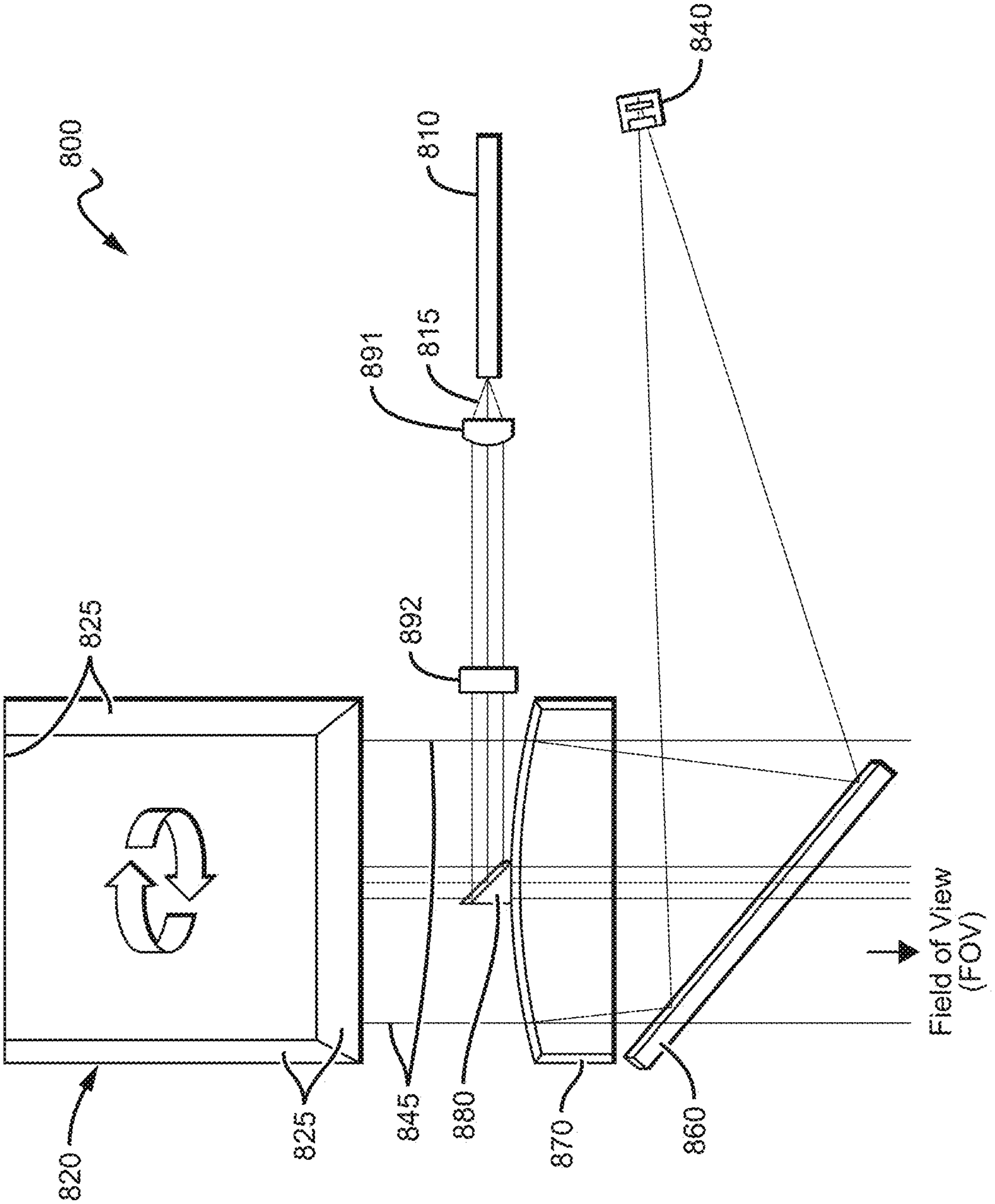

800
810
815
891
892
840
825
825
820
845
880
870
860
Field of View
(FOV)

FIG. 8

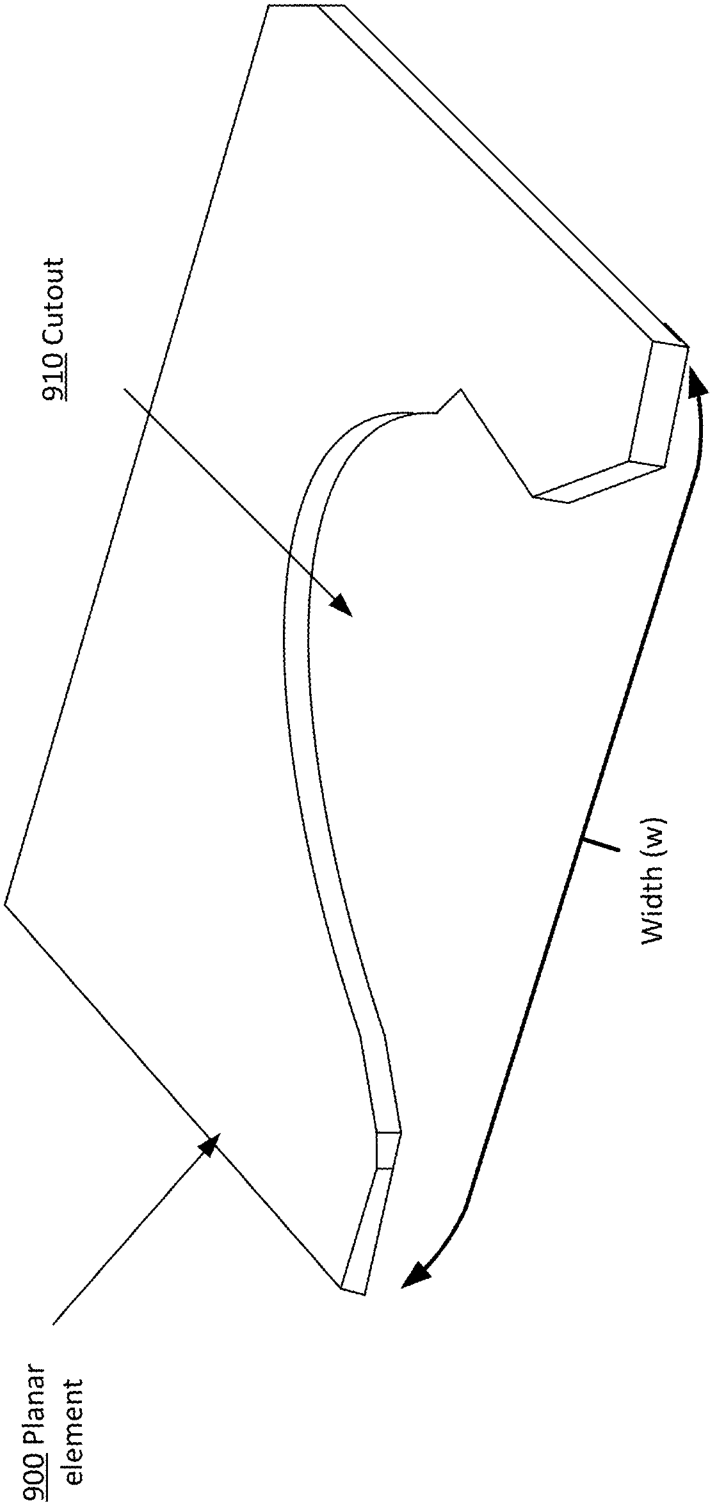


FIG. 9

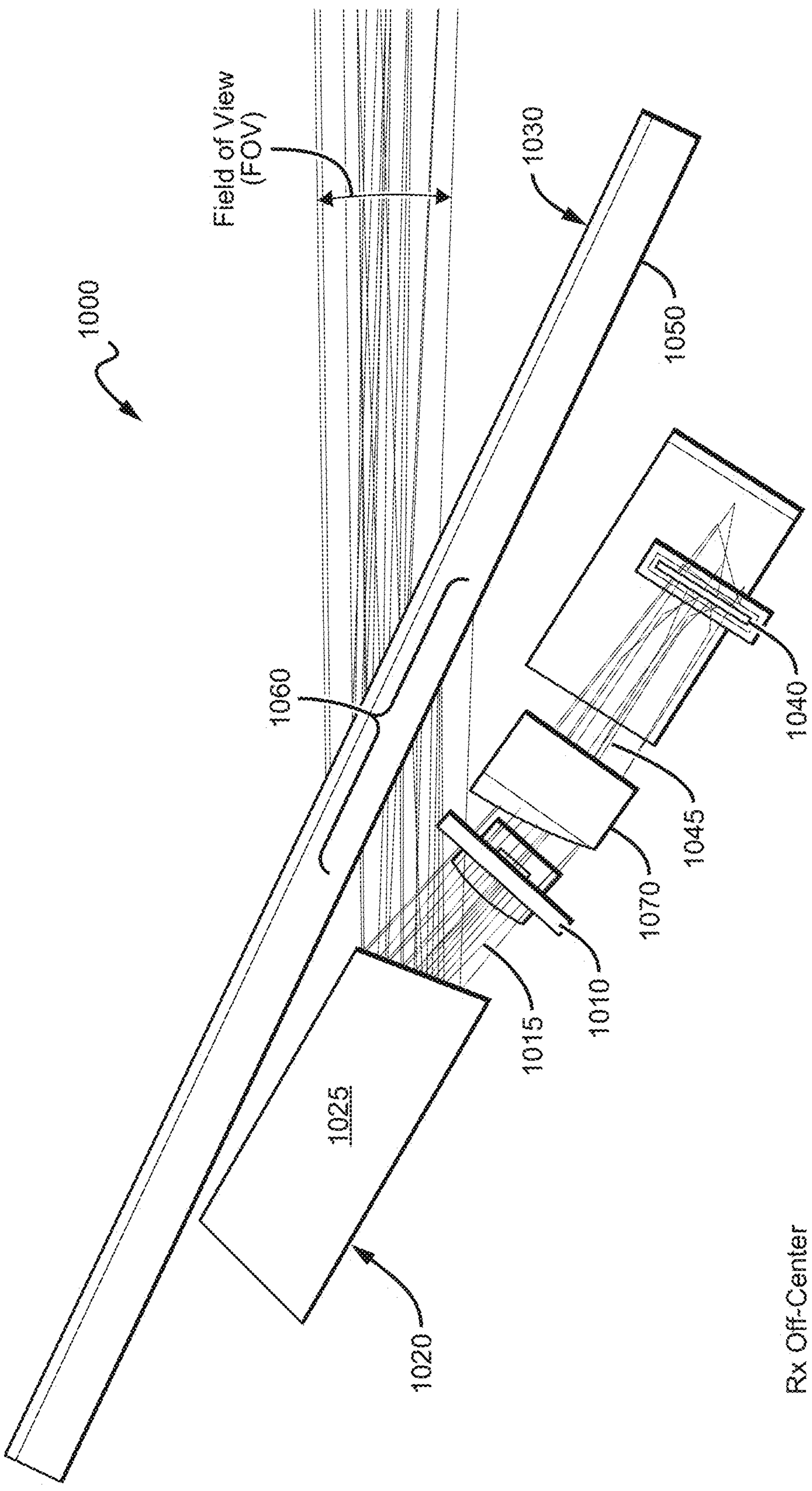

1000
Field of View (FOV)
1030
1050
1060
1040
1045
1070
1010
1015
1025
1020
Rx Off-Center

FIG. 10

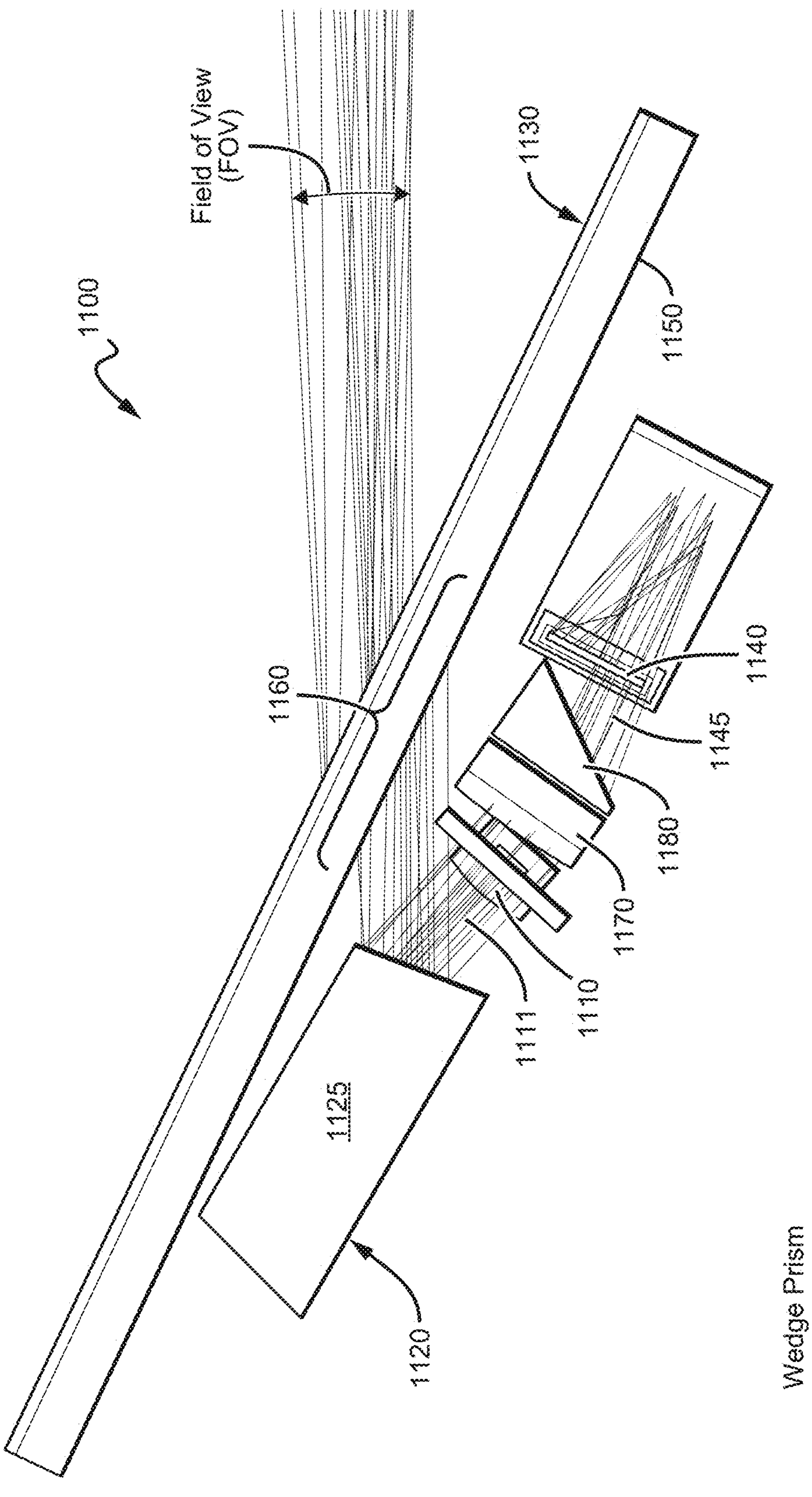

1100
Field of View (FOV)
1130
1150
1160
1140
1145
1180
1170
1110
1111
1125
1120
Wedge Prism

FIG. 11

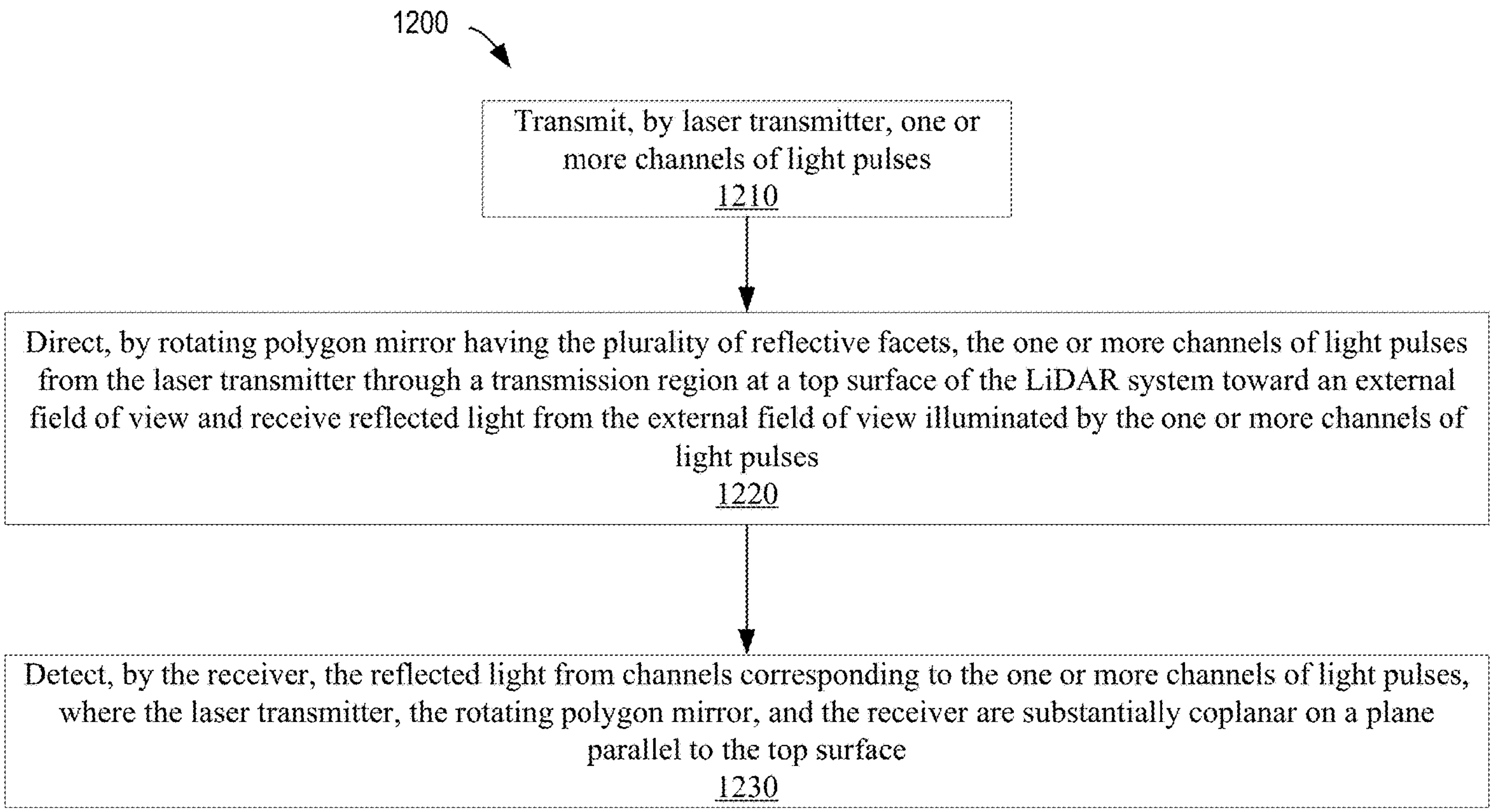

1200
Transmit, by laser transmitter, one or more channels of light pulses
1210
Direct, by rotating polygon mirror having the plurality of reflective facets, the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the LiDAR system toward an external field of view and receive reflected light from the external field of view illuminated by the one or more channels of light pulses
1220
Detect, by the receiver, the reflected light from channels corresponding to the one or more channels of light pulses, where the laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface
1230

FIG. 12

THIN PROFILE WINDSHIELD MOUNTED LIDAR SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Ser. No. 63/450,064, filed Mar. 5, 2023, entitled "THIN PROFILE WINDSHIELD MOUNTED LIDAR SYSTEM," the content of which is hereby incorporated by reference in its entirety for all purposes.

FIELD OF THE TECHNOLOGY

[0002] This disclosure relates generally to light transmission/detection and, more particularly, to a system of light ranging and detection (LiDAR).

BACKGROUND

[0003] Light detection and ranging (LiDAR) systems use light pulses to create an image or point cloud of the external environment. A LiDAR system may be a scanning or non-scanning system. Some typical scanning LiDAR systems include a light source, a light transmitter, a light steering system, and a light detector. The light source generates a light beam that is directed by the light steering system in particular directions when being transmitted from the LiDAR system. When a transmitted light beam is scattered or reflected by an object, a portion of the scattered or reflected light returns to the LiDAR system to form a return light pulse. The light detector detects the return light pulse. Using the difference between the time that the return light pulse is detected and the time that a corresponding light pulse in the light beam is transmitted, the LiDAR system can determine the distance to the object based on the speed of light. This technique of determining the distance is referred to as the time-of-flight (ToF) technique. The light steering system can direct light beams along different paths to allow the LiDAR system to scan the surrounding environment and produce images or point clouds. A typical non-scanning LiDAR system illuminates an entire field-of-view (FOV) rather than scanning through the FOV. An example of the non-scanning LiDAR system is a flash LiDAR, which can also use the ToF technique to measure the distance to an object. LiDAR systems can also use techniques other than time-of-flight and scanning to measure the surrounding environment.

SUMMARY

[0004] Generally, most automotive LiDAR systems are designed to be mounted externally onto the vehicle, which requires custom windows and a large amount of design and maintenance efforts. There is a growing demand for mounting LiDAR right underneath the front windshield, just like conventional cameras, so that the protrusion from vehicle body can be eliminated, and no additional work is necessary to heat and clean the LiDAR window. However, most LiDAR systems are still bulky with at least 35 mm height, and they are designed to be mounted from the bottom, so they can easily interfere with passenger space and cause inconveniences.

[0005] Thus, there is a need for a thin profile windshield mounted LiDAR system.

[0006] Embodiments of present invention are described below. In various embodiments of the present invention, a system for light ranging and detection (LiDAR) may include a transmitter transmitting one or more light pulses. A rotating polygon mirror may have a plurality of reflective facets. The rotating polygon mirror may direct the one or more light pulses from the transmitter through an opening at a top surface of the LiDAR system toward an external field of view (FOV) and receives reflected light from the external field of view illuminated by the one or more light pulses. A receiver may detect the reflected light. The transmitter, the rotating polygon mirror, and the receiver may be substantially coplanar. This configuration allows the LiDAR system to have a thin profile.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The present application can be best understood by reference to the embodiments described below taken in conjunction with the accompanying drawing figures, in which like parts may be referred to by like numerals.

[0008] FIG. **1** illustrates one or more example LiDAR systems disposed or included in a motor vehicle.

[0009] FIG. **2** is a block diagram illustrating interactions between an example LiDAR system and multiple other systems including a vehicle perception and planning system.

[0010] FIG. **3** is a block diagram illustrating an example LiDAR system.

[0011] FIG. **4**A is a block diagram illustrating an example fiber-based laser source.

[0012] FIG. **4**B is a block diagram illustrating an example semiconductor-based laser source.

[0013] FIGS. **5**A-**5**C illustrate an example LiDAR system using pulse signals to measure distances to objects disposed in a field-of-view (FOV).

[0014] FIG. **6** is a block diagram illustrating an example apparatus used to implement systems, apparatus, and methods in various embodiments.

[0015] FIG. **7** is a diagram illustrating a side view of an exemplary LiDAR system in accordance with various embodiments.

[0016] FIG. **8** is a diagram illustrating a bottom-up view of an exemplary LiDAR system in accordance with various embodiments.

[0017] FIG. **9** is a diagram illustrating a planar element of an exemplary LiDAR system in accordance with various embodiments.

[0018] FIG. **10** is a diagram illustrating a side view of an exemplary LiDAR system having an off-center receiver element in accordance with various embodiments.

[0019] FIG. **11** is a diagram illustrating a side view of an exemplary LiDAR system in accordance with various embodiments.

[0020] FIG. **12** is a flow diagram for a process of using a LiDAR system in accordance with various embodiments.

DETAILED DESCRIPTION

[0021] To provide a more thorough understanding of various embodiments of the present invention, the following description sets forth numerous specific details, such as specific configurations, parameters, examples, and the like. It should be recognized, however, that such description is not intended as a limitation on the scope of the present invention but is intended to provide a better description of the exemplary embodiments.

[0022] Throughout the specification and claims, the following terms take the meanings explicitly associated herein, unless the context clearly dictates otherwise:

[0023] The phrase "in one embodiment" as used herein does not necessarily refer to the same embodiment, though it may. Thus, as described below, various embodiments of the disclosure may be readily combined, without departing from the scope or spirit of the invention.

[0024] As used herein, the term "or" is an inclusive "or" operator and is equivalent to the term "and/or," unless the context clearly dictates otherwise.

[0025] The term "based on" is not exclusive and allows for being based on additional factors not described unless the context clearly dictates otherwise.

[0026] As used herein, and unless the context dictates otherwise, the term "coupled to" is intended to include both direct coupling (in which two elements that are coupled to each other contact each other) and indirect coupling (in which at least one additional element is located between the two elements). Therefore, the terms "coupled to" and "coupled with" are used synonymously. Within the context of a networked environment where two or more components or devices are able to exchange data, the terms "coupled to" and "coupled with" are also used to mean "communicatively coupled with", possibly via one or more intermediary devices. The components or devices can be optical, mechanical, and/or electrical devices.

[0027] Although the following description uses terms "first," "second," etc. to describe various elements, these elements should not be limited by the terms. These terms are only used to distinguish one element from another. For example, a first sensor could be termed a second sensor and, similarly, a second sensor could be termed a first sensor, without departing from the scope of the various described examples. The first sensor and the second sensor can both be sensors and, in some cases, can be separate and different sensors.

[0028] In addition, throughout the specification, the meaning of "a", "an", and "the" includes plural references, and the meaning of "in" includes "in" and "on".

[0029] Although some of the various embodiments presented herein constitute a single combination of inventive elements, it should be appreciated that the inventive subject matter is considered to include all possible combinations of the disclosed elements. As such, if one embodiment comprises elements A, B, and C, and another embodiment comprises elements B and D, then the inventive subject matter is also considered to include other remaining combinations of A, B, C, or D, even if not explicitly discussed herein. Further, the transitional term "comprising" means to have as parts or members, or to be those parts or members. As used herein, the transitional term "comprising" is inclusive or open-ended and does not exclude additional, unrecited elements or method steps.

[0030] As used in the description herein and throughout the claims that follow, when a system, engine, server, device, module, or other computing element is described as being configured to perform or execute functions on data in a memory, the meaning of "configured to" or "programmed to" is defined as one or more processors or cores of the computing element being programmed by a set of software instructions stored in the memory of the computing element to execute the set of functions on target data or data objects stored in the memory.

[0031] It should be noted that any language directed to a computer should be read to include any suitable combination of computing devices or network platforms, including servers, interfaces, systems, databases, agents, peers, engines, controllers, modules, or other types of computing devices operating individually or collectively. One should appreciate the computing devices comprise a processor configured to execute software instructions stored on a tangible, non-transitory computer readable storage medium (e.g., hard drive, FPGA, PLA, solid state drive, RAM, flash, ROM, or any other volatile or non-volatile storage devices). The software instructions configure or program the computing device to provide the roles, responsibilities, or other functionality as discussed below with respect to the disclosed apparatus. Further, the disclosed technologies can be embodied as a computer program product that includes a non-transitory computer readable medium storing the software instructions that causes a processor to execute the disclosed steps associated with implementations of computer-based algorithms, processes, methods, or other instructions. In some embodiments, the various servers, systems, databases, or interfaces exchange data using standardized protocols or algorithms, possibly based on HTTP, HTTPS, AES, public-private key exchanges, web service APIs, known financial transaction protocols, or other electronic information exchanging methods. Data exchanges among devices can be conducted over a packet-switched network, the Internet, LAN, WAN, VPN, or other type of packet switched network; a circuit switched network; cell switched network; or other type of network.

[0032] Generally, most automotive LiDAR systems are designed to be mounted externally onto a vehicle, which can require custom windows or windshields and significant design and maintenance efforts to achieve and implement. There is a growing demand for LiDAR systems that can be mounted behind a front windshield or window of a vehicle, similar to how a conventional camera or optical lens could be mounted, so that the protrusion from a vehicle body caused by conventionally mounted LiDAR systems can be eliminated. Further, a vehicle windshield or window mounting point may obviate the additional work is necessary to heat and clean the LiDAR window. However, most LiDAR systems are still bulky with at least 35 mm height, and they are designed to be mounted from the bottom, so they can easily interfere with passenger space and cause other inconveniences if mounted behind a front windshield or window.

[0033] Thus, there is a need for a thin profile windshield-mounted LiDAR system.

[0034] Embodiments of present invention are described below. In various embodiments, a system for light ranging and detection (LiDAR) comprises a laser transmitter transmitting one or more channels of light pulses. A rotating polygon mirror having a plurality of reflective facets directs the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the system toward an external field of view and receives reflected light from the external field of view illuminated by the one or more channels of light pulses. A receiver detects the reflected light from channels corresponding to the one or more channels of light pulses. The laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface. This configuration allows the LiDAR system to have a thin profile.

[0035] FIG. **1** illustrates one or more example LiDAR systems **110** and **120**A-**120**I disposed or included in a motor vehicle **100**. Vehicle **100** can be a car, a sport utility vehicle (SUV), a truck, a train, a wagon, a bicycle, a motorcycle, a tricycle, a bus, a mobility scooter, a tram, a ship, a boat, an underwater vehicle, an airplane, a helicopter, an unmanned aviation vehicle (UAV), a spacecraft, etc. Motor vehicle **100** can be a vehicle having any automated level. For example, motor vehicle **100** can be a partially automated vehicle, a highly automated vehicle, a fully automated vehicle, or a driverless vehicle. A partially automated vehicle can perform some driving functions without a human driver's intervention. For example, a partially automated vehicle can perform blind-spot monitoring, lane keeping and/or lane changing operations, automated emergency braking, smart cruising and/or traffic following, or the like. Certain operations of a partially automated vehicle may be limited to specific applications or driving scenarios (e.g., limited to only freeway driving). A highly automated vehicle can generally perform all operations of a partially automated vehicle but with less limitations. A highly automated vehicle can also detect its own limits in operating the vehicle and ask the driver to take over the control of the vehicle when necessary. A fully automated vehicle can perform all vehicle operations without a driver's intervention but can also detect its own limits and ask the driver to take over when necessary. A driverless vehicle can operate on its own without any driver intervention.

[0036] In typical configurations, motor vehicle **100** comprises one or more LiDAR systems **110** and **120**A-**120**I. Each of LiDAR systems **110** and **120**A-**120**I can be a scanning-based LiDAR system and/or a non-scanning LiDAR system (e.g., a flash LiDAR). A scanning-based LiDAR system scans one or more light beams in one or more directions (e.g., horizontal and vertical directions) to detect objects in a field-of-view (FOV). A non-scanning based LiDAR system transmits laser light to illuminate an FOV without scanning. For example, a flash LiDAR is a type of non-scanning based LiDAR system. A flash LiDAR can transmit laser light to simultaneously illuminate an FOV using a single light pulse or light shot.

[0037] A LiDAR system is a frequently used sensor of a vehicle that is at least partially automated. In one embodiment, as shown in FIG. **1**, motor vehicle **100** may include a single LiDAR system **110** (e.g., without LiDAR systems **120**A-**120**I) disposed at the highest position of the vehicle (e.g., at the vehicle roof). Disposing LiDAR system **110** at the vehicle roof facilitates a 360-degree scanning around vehicle **100**. In some other embodiments, motor vehicle **100** can include multiple LiDAR systems, including two or more of systems **110** and/or **120**A-**120**I. As shown in FIG. **1**, in one embodiment, multiple LiDAR systems **110** and/or **120**A-**120**I are attached to vehicle **100** at different locations of the vehicle. For example, LiDAR system **120**A is attached to vehicle **100** at the front right corner; LiDAR system **120**B is attached to vehicle **100** at the front center position; LiDAR system **120**C is attached to vehicle **100** at the front left corner; LiDAR system **120**D is attached to vehicle **100** at the right-side rear view mirror; LiDAR system **120**E is attached to vehicle **100** at the left-side rear view mirror; LiDAR system **120**F is attached to vehicle **100** at the back center position; LiDAR system **120**G is attached to vehicle **100** at the back right corner; LiDAR system **120**H is attached to vehicle **100** at the back left corner; and/or LiDAR system **120**I is attached to vehicle **100** at the center towards the backend (e.g., back end of the vehicle roof). It is understood that one or more LiDAR systems can be distributed and attached to a vehicle in any desired manner and FIG. **1** only illustrates one embodiment. As another example, LiDAR systems **120**D and **120**E may be attached to the B-pillars of vehicle **100** instead of the rear-view mirrors. As another example, LiDAR system **120**B may be attached to the windshield of vehicle **100** instead of the front bumper.

[0038] In some embodiments, LiDAR systems **110** and **120**A-**120**I are independent LiDAR systems having their own respective laser sources, control electronics, transmitters, receivers, and/or steering mechanisms. In other embodiments, some of LiDAR systems **110** and **120**A-**120**I can share one or more components, thereby forming a distributed sensor system. In one example, optical fibers are used to deliver laser light from a centralized laser source to all LiDAR systems. For instance, system **110** (or another system that is centrally positioned or positioned anywhere inside the vehicle **100**) includes a light source, a transmitter, and a light detector, but has no steering mechanisms. System **110** may distribute transmission light to each of systems **120**A-**120**I. The transmission light may be distributed via optical fibers. Optical connectors can be used to couple the optical fibers to each of system **110** and **120**A-**120**I. In some examples, one or more of systems **120**A-**120**I include steering mechanisms but no light sources, transmitters, or light detectors. A steering mechanism may include one or more moveable mirrors such as one or more polygon mirrors, one or more single plane mirrors, one or more multi-plane mirrors, or the like. Embodiments of the light source, transmitter, steering mechanism, and light detector are described in more detail below. Via the steering mechanisms, one or more of systems **120**A-**120**I scan light into one or more respective FOVs and receive corresponding return light. The return light is formed by scattering or reflecting the transmission light by one or more objects in the FOVs. Systems **120**A-**120**I may also include collection lens and/or other optics to focus and/or direct the return light into optical fibers, which deliver the received return light to system **110**. System **110** includes one or more light detectors for detecting the received return light. In some examples, system **110** is disposed inside a vehicle such that it is in a temperature-controlled environment, while one or more systems **120**A-**120**I may be at least partially exposed to the external environment.

[0039] FIG. **2** is a block diagram **200** illustrating interactions between vehicle onboard LiDAR system(s) **210** and multiple other systems including a vehicle perception and planning system **220**. LiDAR system(s) **210** can be mounted on or integrated to a vehicle. LiDAR system(s) **210** include sensor(s) that scan laser light to the surrounding environment to measure the distance, angle, and/or velocity of objects. Based on the scattered light that returned to LiDAR system(s) **210**, it can generate sensor data (e.g., image data or 3D point cloud data) representing the perceived external environment.

[0040] LiDAR system(s) **210** can include one or more of short-range LiDAR sensors, medium-range LiDAR sensors, and long-range LiDAR sensors. A short-range LiDAR sensor measures objects located up to about 20-50 meters from the LiDAR sensor. Short-range LiDAR sensors can be used for, e.g., monitoring nearby moving objects (e.g., pedestrians crossing street in a school zone), parking assistance applications, or the like. A medium-range LiDAR sensor measures objects located up to about 70-200 meters from the LiDAR sensor. Medium-range LiDAR sensors can be used for, e.g., monitoring road intersections, assistance for merging onto or leaving a freeway, or the like. A long-range LiDAR sensor measures objects located up to about 200 meters and beyond. Long-range LiDAR sensors are typically used when a vehicle is travelling at a high speed (e.g., on a freeway), such that the vehicle's control systems may only have a few seconds (e.g., 6-8 seconds) to respond to any situations detected by the LiDAR sensor. As shown in FIG. **2**, in one embodiment, the LiDAR sensor data can be provided to vehicle perception and planning system **220** via a communication path **213** for further processing and controlling the vehicle operations. Communication path **213** can be any wired or wireless communication links that can transfer data.

[0041] With reference still to FIG. **2**, in some embodiments, other vehicle onboard sensor(s) **230** are configured to provide additional sensor data separately or together with LiDAR system(s) **210**. Other vehicle onboard sensors **230** may include, for example, one or more camera(s) **232**, one or more radar(s) **234**, one or more ultrasonic sensor(s) **236**, and/or other sensor(s) **238**. Camera(s) **232** can take images and/or videos of the external environment of a vehicle. Camera(s) **232** can take, for example, high-definition (HD) videos having millions of pixels in each frame. A camera includes image sensors that facilitate producing monochrome or color images and videos. Color information may be important in interpreting data for some situations (e.g., interpreting images of traffic lights). Color information may not be available from other sensors such as LiDAR or radar sensors. Camera(s) **232** can include one or more of narrow-focus cameras, wider-focus cameras, side-facing cameras, infrared cameras, fisheye cameras, or the like. The image and/or video data generated by camera(s) **232** can also be provided to vehicle perception and planning system **220** via communication path **233** for further processing and controlling the vehicle operations. Communication path **233** can be any wired or wireless communication links that can transfer data. Camera(s) **232** can be mounted on, or integrated to, a vehicle at any location (e.g., rear-view mirrors, pillars, front grille, and/or back bumpers, etc.).

[0042] Other vehicle onboard sensor(s) **230** can also include radar sensor(s) **234**. Radar sensor(s) **234** use radio waves to determine the range, angle, and velocity of objects. Radar sensor(s) **234** produce electromagnetic waves in the radio or microwave spectrum. The electromagnetic waves reflect off an object and some of the reflected waves return to the radar sensor, thereby providing information about the object's position and velocity. Radar sensor(s) **234** can include one or more of short-range radar(s), medium-range radar(s), and long-range radar(s). A short-range radar measures objects located at about 0.1-30 meters from the radar. A short-range radar is useful in detecting objects located near the vehicle, such as other vehicles, buildings, walls, pedestrians, bicyclists, etc. A short-range radar can be used to detect a blind spot, assist in lane changing, provide rear-end collision warning, assist in parking, provide emergency braking, or the like. A medium-range radar measures objects located at about 30-80 meters from the radar. A long-range radar measures objects located at about 80-200 meters. Medium- and/or long-range radars can be useful in, for example, traffic following, adaptive cruise control, and/or highway automatic braking. Sensor data generated by radar sensor(s) **234** can also be provided to vehicle perception and planning system **220** via communication path **233** for further processing and controlling the vehicle operations. Radar sensor(s) **234** can be mounted on, or integrated to, a vehicle at any location (e.g., rear-view mirrors, pillars, front grille, and/or back bumpers, etc.).

[0043] Other vehicle onboard sensor(s) **230** can also include ultrasonic sensor(s) **236**. Ultrasonic sensor(s) **236** use acoustic waves or pulses to measure objects located external to a vehicle. The acoustic waves generated by ultrasonic sensor(s) **236** are transmitted to the surrounding environment. At least some of the transmitted waves are reflected off an object and return to the ultrasonic sensor(s) **236**. Based on the return signals, a distance of the object can be calculated. Ultrasonic sensor(s) **236** can be useful in, for example, checking blind spots, identifying parking spaces, providing lane changing assistance into traffic, or the like. Sensor data generated by ultrasonic sensor(s) **236** can also be provided to vehicle perception and planning system **220** via communication path **233** for further processing and controlling the vehicle operations. Ultrasonic sensor(s) **236** can be mounted on, or integrated to, a vehicle at any location (e.g., rear-view mirrors, pillars, front grille, and/or back bumpers, etc.).

[0044] In some embodiments, one or more other sensor(s) **238** may be attached in a vehicle and may also generate sensor data. Other sensor(s) **238** may include, for example, global positioning systems (GPS), inertial measurement units (IMU), or the like. Sensor data generated by other sensor(s) **238** can also be provided to vehicle perception and planning system **220** via communication path **233** for further processing and controlling the vehicle operations. It is understood that communication path **233** may include one or more communication links to transfer data between the various sensor(s) **230** and vehicle perception and planning system **220**.

[0045] In some embodiments, as shown in FIG. **2**, sensor data from other vehicle onboard sensor(s) **230** can be provided to vehicle onboard LiDAR system(s) **210** via communication path **231**. LiDAR system(s) **210** may process the sensor data from other vehicle onboard sensor(s) **230**. For example, sensor data from camera(s) **232**, radar sensor(s) **234**, ultrasonic sensor(s) **236**, and/or other sensor (s) **238** may be correlated or fused with sensor data LiDAR system(s) **210**, thereby at least partially offloading the sensor fusion process performed by vehicle perception and planning system **220**. It is understood that other configurations may also be implemented for transmitting and processing sensor data from the various sensors (e.g., data can be transmitted to a cloud or edge computing service provider for processing and then the processing results can be transmitted back to the vehicle perception and planning system **220** and/or LiDAR system **210**).

[0046] With reference still to FIG. **2**, in some embodiments, sensors onboard other vehicle(s) **250** are used to provide additional sensor data separately or together with LiDAR system(s) **210**. For example, two or more nearby vehicles may have their own respective LiDAR sensor(s), camera(s), radar sensor(s), ultrasonic sensor(s), etc. Nearby vehicles can communicate and share sensor data with one another. Communications between vehicles are also referred to as V2V (vehicle to vehicle) communications. For example, as shown in FIG. **2**, sensor data generated by other vehicle(s) **250** can be communicated to vehicle perception and planning system **220** and/or vehicle onboard LiDAR system(s) **210**, via communication path **253** and/or communication path **251**, respectively. Communication paths **253** and **251** can be any wired or wireless communication links that can transfer data.

[0047] Sharing sensor data facilitates a better perception of the environment external to the vehicles. For instance, a first vehicle may not sense a pedestrian that is behind a second vehicle but is approaching the first vehicle. The second vehicle may share the sensor data related to this pedestrian with the first vehicle such that the first vehicle can have additional reaction time to avoid collision with the pedestrian. In some embodiments, similar to data generated by sensor(s) **230**, data generated by sensors onboard other vehicle(s) **250** may be correlated or fused with sensor data generated by LiDAR system(s) **210** (or with other LiDAR systems located in other vehicles), thereby at least partially offloading the sensor fusion process performed by vehicle perception and planning system **220**.

[0048] In some embodiments, intelligent infrastructure system(s) **240** are used to provide sensor data separately or together with LiDAR system(s) **210**. Certain infrastructures may be configured to communicate with a vehicle to convey information and vice versa. Communications between a vehicle and infrastructures are generally referred to as V2I (vehicle to infrastructure) communications. For example, intelligent infrastructure system(s) **240** may include an intelligent traffic light that can convey its status to an approaching vehicle in a message such as "changing to yellow in 5 seconds." Intelligent infrastructure system(s) **240** may also include its own LiDAR system mounted near an intersection such that it can convey traffic monitoring information to a vehicle. For example, a left-turning vehicle at an intersection may not have sufficient sensing capabilities because some of its own sensors may be blocked by traffic in the opposite direction. In such a situation, sensors of intelligent infrastructure system(s) **240** can provide useful data to the left-turning vehicle. Such data may include, for example, traffic conditions, information of objects in the direction the vehicle is turning to, traffic light status and predictions, or the like. These sensor data generated by intelligent infrastructure system(s) **240** can be provided to vehicle perception and planning system **220** and/or vehicle onboard LiDAR system(s) **210**, via communication paths **243** and/or **241**, respectively. Communication paths **243** and/or **241** can include any wired or wireless communication links that can transfer data. For example, sensor data from intelligent infrastructure system(s) **240** may be transmitted to LiDAR system(s) **210** and correlated or fused with sensor data generated by LiDAR system(s) **210**, thereby at least partially offloading the sensor fusion process performed by vehicle perception and planning system **220**. V2V and V2I communications described above are examples of vehicle-to-X (V2X) communications, where the "X" represents any other devices, systems, sensors, infrastructure, or the like that can share data with a vehicle.

[0049] With reference still to FIG. **2**, via various communication paths, vehicle perception and planning system **220** receives sensor data from one or more of LiDAR system(s) **210**, other vehicle onboard sensor(s) **230**, other vehicle(s) **250**, and/or intelligent infrastructure system(s) **240**. In some embodiments, different types of sensor data are correlated and/or integrated by a sensor fusion sub-system **222**. For example, sensor fusion sub-system **222** can generate a 360-degree model using multiple images or videos captured by multiple cameras disposed at different positions of the vehicle. Sensor fusion sub-system **222** obtains sensor data from different types of sensors and uses the combined data to perceive the environment more accurately. For example, a vehicle onboard camera **232** may not capture a clear image because it is facing the Sun or a light source (e.g., another vehicle's headlight during nighttime) directly. A LiDAR system **210** may not be affected as much and therefore sensor fusion sub-system **222** can combine sensor data provided by both camera **232** and LiDAR system **210**, and use the sensor data provided by LiDAR system **210** to compensate the unclear image captured by camera **232**. As another example, in rainy or foggy weather, a radar sensor **234** may work better than a camera **232** or a LiDAR system **210**. Accordingly, sensor fusion sub-system **222** may use sensor data provided by the radar sensor **234** to compensate the sensor data provided by camera **232** or LiDAR system **210**.

[0050] In other examples, sensor data generated by other vehicle onboard sensor(s) **230** may have a lower resolution (e.g., radar sensor data) and thus may need to be correlated and confirmed by LiDAR system(s) **210**, which usually has a higher resolution. For example, a sewage cover (also referred to as a manhole cover) may be detected by radar sensor **234** as an object towards which a vehicle is approaching. Due to the low-resolution nature of radar sensor **234**, vehicle perception and planning system **220** may not be able to determine whether the object is an obstacle that the vehicle needs to avoid. High-resolution sensor data generated by LiDAR system(s) **210** thus can be used to correlated and confirm that the object is a sewage cover and causes no harm to the vehicle.

[0051] Vehicle perception and planning system **220** further comprises an object classifier **223**. Using raw sensor data and/or correlated/fused data provided by sensor fusion sub-system **222**, object classifier **223** can use any computer vision techniques to detect and classify the objects and estimate the positions of the objects. In some embodiments, object classifier **223** can use machine-learning based techniques to detect and classify objects. Examples of the machine-learning based techniques include utilizing algorithms such as region-based convolutional neural networks (R-CNN), Fast R-CNN, Faster R-CNN, histogram of oriented gradients (HOG), region-based fully convolutional network (R-FCN), single shot detector (SSD), spatial pyramid pooling (SPP-net), and/or You Only Look Once (Yolo).

[0052] Vehicle perception and planning system **220** further comprises a road detection sub-system **224**. Road detection sub-system **224** localizes the road and identifies objects and/or markings on the road. For example, based on raw or fused sensor data provided by radar sensor(s) **234**, camera(s) **232**, and/or LiDAR system(s) **210**, road detection sub-system **224** can build a 3D model of the road based on machine-learning techniques (e.g., pattern recognition algorithms for identifying lanes). Using the 3D model of the road, road detection sub-system **224** can identify objects (e.g., obstacles or debris on the road) and/or markings on the road (e.g., lane lines, turning marks, crosswalk marks, or the like).

[0053] Vehicle perception and planning system **220** further comprises a localization and vehicle posture sub-system **225**. Based on raw or fused sensor data, localization and vehicle posture sub-system **225** can determine the position of the vehicle and the vehicle's posture. For example, using sensor data from LiDAR system(s) **210**, camera(s) **232**, and/or GPS data, localization and vehicle posture sub-system **225** can determine an accurate position of the vehicle on the road and the vehicle's six degrees of freedom (e.g., whether the vehicle is moving forward or backward, up or down, and left or right). In some embodiments, high-definition (HD) maps are used for vehicle localization. HD maps can provide highly detailed, three-dimensional, computerized maps that pinpoint a vehicle's location. For instance, using the HD maps, localization and vehicle posture sub-system **225** can determine precisely the vehicle's current position (e.g., which lane of the road the vehicle is currently in, how close it is to a curb or a sidewalk) and predict vehicle's future positions.

[0054] Vehicle perception and planning system **220** further comprises obstacle predictor **226**. Objects identified by object classifier **223** can be stationary (e.g., a light pole, a road sign) or dynamic (e.g., a moving pedestrian, bicycle, another car). For moving objects, predicting their moving path or future positions can be important to avoid collision. Obstacle predictor **226** can predict an obstacle trajectory and/or warn the driver or the vehicle planning sub-system **228** about a potential collision. For example, if there is a high likelihood that the obstacle's trajectory intersects with the vehicle's current moving path, obstacle predictor **226** can generate such a warning. Obstacle predictor **226** can use a variety of techniques for making such a prediction. Such techniques include, for example, constant velocity or acceleration models, constant turn rate and velocity/acceleration models, Kalman Filter and Extended Kalman Filter based models, recurrent neural network (RNN) based models, long short-term memory (LSTM) neural network based models, encoder-decoder RNN models, or the like.

[0055] With reference still to FIG. **2**, in some embodiments, vehicle perception and planning system **220** further comprises vehicle planning sub-system **228**. Vehicle planning sub-system **228** can include one or more planners such as a route planner, a driving behaviors planner, and a motion planner. The route planner can plan the route of a vehicle based on the vehicle's current location data, target location data, traffic information, etc. The driving behavior planner adjusts the timing and planned movement based on how other objects might move, using the obstacle prediction results provided by obstacle predictor **226**. The motion planner determines the specific operations the vehicle needs to follow. The planning results are then communicated to vehicle control system **280** via vehicle interface **270**. The communication can be performed through communication paths **227** and **271**, which include any wired or wireless communication links that can transfer data.

[0056] Vehicle control system **280** controls the vehicle's steering mechanism, throttle, brake, etc., to operate the vehicle according to the planned route and movement. In some examples, vehicle perception and planning system **220** may further comprise a user interface **260**, which provides a user (e.g., a driver) access to vehicle control system **280** to, for example, override or take over control of the vehicle when necessary. User interface **260** may also be separate from vehicle perception and planning system **220**. User interface **260** can communicate with vehicle perception and planning system **220**, for example, to obtain and display raw or fused sensor data, identified objects, vehicle's location/posture, etc. These displayed data can help a user to better operate the vehicle. User interface **260** can communicate with vehicle perception and planning system **220** and/or vehicle control system **280** via communication paths **221** and **261** respectively, which include any wired or wireless communication links that can transfer data. It is understood that the various systems, sensors, communication links, and interfaces in FIG. **2** can be configured in any desired manner and not limited to the configuration shown in FIG. **2**.

[0057] FIG. **3** is a block diagram illustrating an example LiDAR system **300**. LiDAR system **300** can be used to implement LiDAR systems **110**, **120**A-**120**I, and/or **210** shown in FIGS. **1** and **2**. In one embodiment, LiDAR system **300** comprises a light source **310**, a transmitter **320**, an optical receiver and light detector **330**, a steering system **340**, and control circuitry **350**. These components are coupled together using communications paths **312**, **314**, **322**, **332**, **342**, **352**, **362**, and **372**. These communications paths include communication links (wired or wireless, 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, buses, or optical fibers, the communication paths can also be wireless channels or free-space optical paths so that no physical communication medium is present. For example, in one embodiment of LiDAR system **300**, communication path **314** between light source **310** and transmitter **320** may be implemented using one or more optical fibers. Communication paths **332** and **352** may represent optical paths implemented using free space optical components and/or optical fibers. And communication paths **312**, **322**, **342**, and **362** may be implemented using one or more electrical wires that carry electrical signals. The communications paths can also include one or more of the above types of communication mediums (e.g., they can include an optical fiber and a free-space optical component, or include one or more optical fibers and one or more electrical wires).

[0058] In some embodiments, LiDAR system **300** can be a coherent LiDAR system. One example is a frequency-modulated continuous-wave (FMCW) LiDAR. Coherent LiDARs detect objects by mixing return light from the objects with light from the coherent laser transmitter. Thus, as shown in FIG. **3**, if LiDAR system **300** is a coherent LiDAR, it may include a route **372** providing a portion of transmission light from transmitter **320** to optical receiver and light detector **330**. Route **372** may include one or more optics (e.g., optical fibers, lens, mirrors, etc.) for providing the light from transmitter **320** to optical receiver and light detector **330**. The transmission light provided by transmitter **320** may be modulated light and can be split into two portions. One portion is transmitted to the FOV, while the second portion is sent to the optical receiver and light detector **330** of the LiDAR system **300**. The second portion is also referred to as the light that is kept local (LO) to the LiDAR system **300**. The transmission light is scattered or reflected by various objects in the FOV and at least a portion of it forms return light. The return light is subsequently detected and interferometrically recombined with the second portion of the transmission light that was kept local. Coherent LiDAR provides a means of optically sensing an object's range as well as its relative velocity along the line-of-sight (LOS).

[0059] LiDAR system **300** can also include other components not depicted in FIG. **3**, such as power buses, power supplies, LED indicators, switches, etc. Additionally, other communication connections among components may be present, such as a direct connection between light source **310** and optical receiver and light detector **330** to provide a reference signal so that the time from when a light pulse is transmitted until a return light pulse is detected can be accurately measured.

[0060] Light source **310** outputs laser light for illuminating objects in a field of view (FOV). The laser light can be infrared light having a wavelength in the range of 700 nm to 1 mm. Light source **310** can be, for example, a semiconductor-based laser (e.g., a diode laser) and/or a fiber-based laser. A semiconductor-based laser can be, for example, an edge emitting laser (EEL), a vertical cavity surface emitting laser (VCSEL), an external-cavity diode laser, a vertical-external-cavity surface-emitting laser, a distributed feedback (DFB) laser, a distributed Bragg reflector (DBR) laser, an interband cascade laser, a quantum cascade laser, a quantum well laser, a double heterostructure laser, or the like. A fiber-based laser is a laser in which the active gain medium is an optical fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium, and/or holmium. In some embodiments, a fiber laser is based on double-clad fibers, in which the gain medium forms the core of the fiber surrounded by two layers of cladding. The double-clad fiber allows the core to be pumped with a high-power beam, thereby enabling the laser source to be a high-power fiber laser source.

[0061] In some embodiments, light source **310** comprises a master oscillator (also referred to as a seed laser) and power amplifier (MOPA). The power amplifier amplifies the output power of the seed laser. The power amplifier can be a fiber amplifier, a bulk amplifier, or a semiconductor optical amplifier. The seed laser can be a diode laser (e.g., a Fabry-Perot cavity laser, a distributed feedback laser), a solid-state bulk laser, or a tunable external-cavity diode laser. In some embodiments, light source **310** can be an optically pumped microchip laser. Microchip lasers are alignment-free monolithic solid-state lasers where the laser crystal is directly contacted with the end mirrors of the laser resonator. A microchip laser is typically pumped with a laser diode (directly or using a fiber) to obtain the desired output power. A microchip laser can be based on neodymium-doped yttrium aluminum garnet ($Y_3Al_5O_{12}$) laser crystals (i.e., Nd:YAG), or neodymium-doped vanadate (i.e., ND:YVO_4) laser crystals. In some examples, light source **310** may have multiple amplification stages to achieve a high-power gain such that the laser output can have high power, thereby enabling the LiDAR system to have a long scanning range. In some examples, the power amplifier of light source **310** can be controlled such that the power gain can be varied to achieve any desired laser output power.

[0062] FIG. **4**A is a block diagram illustrating an example fiber-based laser source **400** having a seed laser and one or more pumps (e.g., laser diodes) for pumping desired output power. Fiber-based laser source **400** is an example of light source **310** depicted in FIG. **3**. In some embodiments, fiber-based laser source **400** comprises a seed laser **402** configured to generate initial light pulses of one or more wavelengths (e.g., infrared wavelengths such as 1550 nm), which are provided to a wavelength-division multiplexor (WDM) **404** via an optical fiber **403**. Fiber-based laser source **400** further comprises a pump **406** for providing laser power (e.g., of a different wavelength, such as 980 nm) to WDM **404** via an optical fiber **405**. WDM **404** multiplexes the light pulses provided by seed laser **402** and the laser power provided by pump **406** onto a single optical fiber **407**. The output of WDM **404** can then be provided to one or more pre-amplifier(s) **408** via optical fiber **407**. Pre-amplifier(s) **408** can be optical amplifier(s) that amplify optical signals (e.g., with about 10-30 dB gain). In some embodiments, pre-amplifier(s) **408** are low noise amplifiers. Pre-amplifier(s) **408** output to an optical combiner **410** via an optical fiber **409**. Combiner **410** combines the output laser light of pre-amplifier(s) **408** with the laser power provided by pump **412** via an optical fiber **411**. Combiner **410** can combine optical signals having the same wavelength or different wavelengths. One example of a combiner is a WDM. Combiner **410** provides combined optical signals to a booster amplifier **414**, which produces output light pulses via optical fiber **415**. The booster amplifier **414** provides further amplification of the optical signals (e.g., another 20-40 dB). The output light pulses can then be transmitted to transmitter **320** and/or steering mechanism **340** (shown in FIG. **3**). It is understood that FIG. **4**A illustrates one example configuration of fiber-based laser source **400**. Laser source **400** can have many other configurations using different combinations of one or more components shown in FIG. **4**A and/or other components not shown in FIG. **4**A (e.g., other components such as power supplies, lens(es), filters, splitters, combiners, etc.).

[0063] In some variations, fiber-based laser source **400** can be controlled (e.g., by control circuitry **350**) to produce pulses of different amplitudes based on the fiber gain profile of the fiber used in fiber-based laser source **400**. Communication path **312** couples fiber-based laser source **400** to control circuitry **350** (shown in FIG. **3**) so that components of fiber-based laser source **400** can be controlled by or otherwise communicate with control circuitry **350**. Alternatively, fiber-based laser source **400** may include its own dedicated controller. Instead of control circuitry **350** communicating directly with components of fiber-based laser source **400**, a dedicated controller of fiber-based laser source **400** communicates with control circuitry **350** and controls and/or communicates with the components of fiber-based laser source **400**. Fiber-based laser source **400** can also include other components not shown, such as one or more power connectors, power supplies, and/or power lines.

[0064] FIG. **4**B is a block diagram illustrating an example semiconductor-based laser source **440**. Semiconductor-based laser source **440** is an example of light source **310** depicted in FIG. **3**. In the example shown in FIG. **4**B, laser source **440** is a Vertical-Cavity Surface-Emitting Laser (VCSEL), which is a type of semiconductor laser diode with a distinctive structure that allows it to emit light vertically from the surface of the chip, rather than through the edge of the chip like the edge-emitting laser (EEL) diodes. VCSELs have advantages like high-speed operation and easy integration into semiconductor devices. FIG. **4**B shows a cross-sectional view of an example VCSEL **440**. In this example, the VCSEL **440** includes a metal contact layer **442**, an upper Bragg reflector **444**, an active region **446**, a lower Bragg reflector **448**, a substrate **450**, and another metal contact **452**. In the VCSEL **440**, the metal contacts **442** and **452** are for making electrical contacts so that electrical current and/or voltage can be provided to VCSEL **440** for generating laser light. The substrate layer **450** is a semiconductor substrate, which can be, for example, a gallium arsenide (GaAs) substrate. VCSEL **440** uses a laser resonator, which includes two distributed Bragg reflector (DBR) reflectors (i.e., upper Bragg reflector **444** and lower Bragg reflector **448**) with an active region **446** sandwiched between the DBR reflectors. The active region **446** includes, for example, one or more quantum wells for the laser light generation. The planar DBR-reflectors can be mirrors having layers with alternating high and low refractive indices. Each layer has a thickness of a quarter of the laser wavelength in the material, yielding intensity reflectivities above e.g., 99%. High reflectivity mirrors in VCSELs can balance the short axial length of the gain region. In one example of VCSEL **440**, the upper and lower DBR reflectors **444** and **448** can be doped as p-type and n-type materials, forming a diode junction. In another example, the p-type and n-type regions may be embedded between the reflectors, requiring a more complex semiconductor process to make electrical contact to the active region, but eliminating electrical power loss in the DBR structure. The active region **446** is sandwiched between the DBR reflectors **444** and **448** of the VCSEL **440**. The active region is where the laser light generation occurs. The active region **446** typically has a quantum well or quantum dot structure, which contains the gain medium responsible for light amplification. When an electric current is applied to the active region **446**, it generates photons by stimulated emission. The distance between the upper and lower DBR reflectors **444** and **448** defines the cavity length of the VCSEL **440**. The cavity length in turn determines the wavelength of the emitted light and influences the laser's performance characteristics. When an electrical current is applied to the VCSEL **440**, it generates light that bounces between the DBR reflectors **444** and **448** and exits the VCSEL **440** through, for example, the lower DBR reflector **448**, producing a highly coherent and vertically emitted laser beam **454**. VCSEL **440** can provide an improved beam quality, low threshold current, and the ability to produce single-mode or multi-mode output.

[0065] In some variations, VCSEL **440** can be controlled (e.g., by control circuitry **350**) to produce pulses of different amplitudes. Communication path **312** couples VCSEL **440** to control circuitry **350** (shown in FIG. **3**) so that components of VCSEL **440** can be controlled by or otherwise communicate with control circuitry **350**. Alternatively, VCSEL **440** may include its own dedicated controller. Instead of control circuitry **350** communicating directly with components of VCSEL **400**, a dedicated controller of VCSEL **440** communicates with control circuitry **350** and controls and/or communicates with the components of VCSEL **440**. VCSEL **440** can also include other components not shown, such as one or more power connectors, power supplies, and/or power lines.

[0066] VCSEL **440** can be used to generate laser pulses or continuous wave (CW) lasers. To generate laser pulses, control circuitry **350** modulates the current supplied to the VCSEL **440**. By rapidly turning the supply current on and off, pulses of laser light can be generated. The duration, repetition rate, and shape of the pulses can be controlled by adjusting the modulation parameters. As another example, VCSEL **440** can also be a mode-locked VCSEL that uses a combination of current modulation and optical feedback to obtain ultra-short pulses. The mode-locked VCSEL may also be controlled to synchronize the phases of the laser modes to produce very short and high-intensity pulses. As another example, VCSEL **440** can use Q-Switching techniques, which includes an optical switch in the laser cavity, temporarily blocking the lasing action and allows energy to build up in the cavity. When the switch is opened, a high-intensity pulse is emitted. As another example, VCSEL **440** can also have external modulation performed by an external modulator (not shown), such as an electro-optic or acousto-optic modulator. The external modulation can be used in combination with the VCSEL itself to create pulsed output. The external modulator can be used to control the pulse duration and repetition rate. The type of VCSEL used as at least a part of light source **310** depends on the application and the required pulse characteristics, such as pulse duration, repetition rate, and peak power.

[0067] Referencing FIG. **3**, typical operating wavelengths of light source **310** comprise, for example, about 850 nm, about 905 nm, about 940 nm, about 1064 nm, and about 1550 nm. For laser safety, the upper limit of maximum usable laser power is set by the U.S. FDA (U.S. Food and Drug Administration) regulations. The optical power limit at 1550 nm wavelength is much higher than those of the other aforementioned wavelengths. Further, at 1550 nm, the optical power loss in a fiber is low. There characteristics of the 1550 nm wavelength make it more beneficial for long-range LiDAR applications. The amount of optical power output from light source **310** can be characterized by its peak power, average power, pulse energy, and/or the pulse energy density. The peak power is the ratio of pulse energy to the width of the pulse (e.g., full width at half maximum or FWHM). Thus, a smaller pulse width can provide a larger peak power for a fixed amount of pulse energy. A pulse width can be in the range of nanosecond or picosecond. The average power is the product of the energy of the pulse and the pulse repetition rate (PRR). As described in more detail below, the PRR represents the frequency of the pulsed laser light. In general, the smaller the time interval between the pulses, the higher the PRR. The PRR typically corresponds to the maximum range that a LiDAR system can measure. Light source **310** can be configured to produce pulses at high PRR to meet the desired number of data points in a point cloud generated by the LiDAR system. Light source **310** can also be configured to produce pulses at medium or low PRR to meet the desired maximum detection distance. Wall plug efficiency (WPE) is another factor to evaluate the total power consumption, which may be a useful indicator in evaluating the laser efficiency. For example, as shown in FIG. **1**, multiple LiDAR systems may be attached to a vehicle, which may be an electrical-powered vehicle or a vehicle otherwise having limited fuel or battery power supply. Therefore, high WPE and intelligent ways to use laser power are often among the important considerations when selecting and configuring light source **310** and/or designing laser delivery systems for vehicle-mounted LiDAR applications.

[0068] It is understood that the above descriptions provide non-limiting examples of a light source **310**. Light source **310** can be configured to include many other types of light sources (e.g., laser diodes, short-cavity fiber lasers, solid-state lasers, and/or tunable external cavity diode lasers) that are configured to generate one or more light signals at various wavelengths. In some examples, light source **310** comprises amplifiers (e.g., pre-amplifiers and/or booster amplifiers), which can be a doped optical fiber amplifier, a solid-state bulk amplifier, and/or a semiconductor optical amplifier. The amplifiers are configured to receive and amplify light signals with desired gains.

[0069] With reference back to FIG. **3**, LiDAR system **300** further comprises a transmitter **320**. Light source **310** provides laser light (e.g., in the form of a laser beam) to transmitter **320**. The laser light provided by light source **310** can be amplified laser light with a predetermined or controlled wavelength, pulse repetition rate, and/or power level. Transmitter **320** receives the laser light from light source **310** and transmits the laser light to steering mechanism **340** with low divergence. In some embodiments, transmitter **320** can include, for example, optical components (e.g., lens, fibers, mirrors, etc.) for transmitting one or more laser beams to a field-of-view (FOV) directly or via steering mechanism **340**. While FIG. **3** illustrates transmitter **320** and steering mechanism **340** as separate components, they may be combined or integrated as one system in some embodiments. Steering mechanism **340** is described in more detail below.

[0070] Laser beams provided by light source **310** may diverge as they travel to transmitter **320**. Therefore, transmitter **320** often comprises a collimating lens or a lens group configured to collect the diverging laser beams and produce more parallel optical beams with reduced or minimum divergence. The collimated optical beams can then be further directed through various optics such as mirrors and lens. A collimating lens may be, for example, a single plano-convex lens or a lens group. The collimating lens can be configured to achieve any desired properties such as the beam diameter, divergence, numerical aperture, focal length, or the like. A beam propagation ratio or beam quality factor (also referred to as the M^2 factor) is used for measurement of laser beam quality. In many LiDAR applications, it is important to have good laser beam quality in the generated transmitting laser beam. The M^2 factor represents a degree of variation of a beam from an ideal Gaussian beam. Thus, the M^2 factor reflects how well a collimated laser beam can be focused on a small spot, or how well a divergent laser beam can be collimated. Therefore, light source **310** and/or transmitter **320** can be configured to meet, for example, a scan resolution requirement while maintaining the desired M^2 factor.

[0071] One or more of the light beams provided by transmitter **320** are scanned by steering mechanism **340** to a FOV. Steering mechanism **340** scans light beams in multiple dimensions (e.g., in both the horizontal and vertical dimension) to facilitate LiDAR system **300** to map the environment by generating a 3D point cloud. A horizontal dimension can be a dimension that is parallel to the horizon or a surface associated with the LiDAR system or a vehicle (e.g., a road surface). A vertical dimension is perpendicular to the horizontal dimension (i.e., the vertical dimension forms a 90-degree angle with the horizontal dimension). Steering mechanism **340** will be described in more detail below. The laser light scanned to an FOV may be scattered or reflected by an object in the FOV. At least a portion of the scattered or reflected light forms return light that returns to LiDAR system **300**. FIG. **3** further illustrates an optical receiver and light detector **330** configured to receive the return light. Optical receiver and light detector **330** comprises an optical receiver that is configured to collect the return light from the FOV. The optical receiver can include optics (e.g., lens, fibers, mirrors, etc.) for receiving, redirecting, focusing, amplifying, and/or filtering return light from the FOV. For example, the optical receiver often includes a collection lens (e.g., a single plano-convex lens or a lens group) to collect and/or focus the collected return light onto a light detector.

[0072] A light detector detects the return light focused by the optical receiver and generates current and/or voltage signals proportional to the incident intensity of the return light. Based on such current and/or voltage signals, the depth information of the object in the FOV can be derived. One example method for deriving such depth information is based on the direct TOF (time of flight), which is described in more detail below. A light detector may be characterized by its detection sensitivity, quantum efficiency, detector bandwidth, linearity, signal to noise ratio (SNR), overload resistance, interference immunity, etc. Based on the applications, the light detector can be configured or customized to have any desired characteristics. For example, optical receiver and light detector **330** can be configured such that the light detector has a large dynamic range while having good linearity. The light detector linearity indicates the detector's capability of maintaining linear relationship between input optical signal power and the detector's output. A detector having good linearity can maintain a linear relationship over a large dynamic input optical signal range.

[0073] To achieve desired detector characteristics, configurations or customizations can be made to the light detector's structure and/or the detector's material system. Various detector structures can be used for a light detector. For example, a light detector structure can be a PIN based structure, which has an undoped intrinsic semiconductor region (i.e., an "i" region) between a p-type semiconductor and an n-type semiconductor region. Other light detector structures comprise, for example, an APD (avalanche photodiode) based structure, a PMT (photomultiplier tube) based structure, a SiPM (Silicon photomultiplier) based structure, a SPAD (single-photon avalanche diode) based structure, and/or quantum wires. For material systems used in a light detector, Si, InGaAs, and/or Si/Ge based materials can be used. It is understood that many other detector structures and/or material systems can be used in optical receiver and light detector **330**.

[0074] A light detector (e.g., an APD based detector) may have an internal gain such that the input signal is amplified when generating an output signal. However, noise may also be amplified due to the light detector's internal gain. Common types of noise include signal shot noise, dark current shot noise, thermal noise, and amplifier noise. In some embodiments, optical receiver and light detector **330** may include a pre-amplifier that is a low noise amplifier (LNA). In some embodiments, the pre-amplifier may also include a transimpedance amplifier (TIA), which converts a current signal to a voltage signal. For a linear detector system, input equivalent noise or noise equivalent power (NEP) measures how sensitive the light detector is to weak signals. Therefore, they can be used as indicators of the overall system performance. For example, the NEP of a light detector specifies the power of the weakest signal that can be detected and therefore it in turn specifies the maximum range of a LiDAR system. It is understood that various light detector optimization techniques can be used to meet the requirement of LiDAR system **300**. Such optimization techniques may include selecting different detector structures, materials, and/or implementing signal processing techniques (e.g., filtering, noise reduction, amplification, or the like). For example, in addition to, or instead of, using direct detection of return signals (e.g., by using ToF), coherent detection can also be used for a light detector. Coherent detection allows for detecting amplitude and phase information of the received light by interfering the received light with a local oscillator. Coherent detection can improve detection sensitivity and noise immunity.

[0075] FIG. **3** further illustrates that LiDAR system **300** comprises steering mechanism **340**. As described above, steering mechanism **340** directs light beams from transmitter **320** to scan an FOV in multiple dimensions. A steering mechanism is also referred to as a raster mechanism, a scanning mechanism, or simply a light scanner. Scanning light beams in multiple directions (e.g., in both the horizontal and vertical directions) facilitates a LiDAR system to map the environment by generating an image or a 3D point cloud. A steering mechanism can be based on mechanical scanning and/or solid-state scanning. Mechanical scanning uses rotating mirrors to steer the laser beam or physically rotate the LiDAR transmitter and receiver (collectively referred to as transceiver) to scan the laser beam. Solid-state scanning directs the laser beam to various positions through the FOV without mechanically moving any macroscopic components such as the transceiver. Solid-state scanning mechanisms include, for example, optical phased arrays based steering and flash LiDAR based steering. In some embodiments, because solid-state scanning mechanisms do not physically move macroscopic components, the steering performed by a solid-state scanning mechanism may be referred to as effective steering. A LiDAR system using solid-state scanning may also be referred to as a non-mechanical scanning or simply non-scanning LiDAR system (a flash LiDAR system is an example non-scanning LiDAR system).

[0076] Steering mechanism **340** can be used with a transceiver (e.g., transmitter **320** and optical receiver and light detector **330**) to scan the FOV for generating an image or a 3D point cloud. As an example, to implement steering mechanism **340**, a two-dimensional mechanical scanner can be used with a single-point or several single-point transceivers. A single-point transceiver transmits a single light beam or a small number of light beams (e.g., 2-8 beams) to the steering mechanism. A two-dimensional mechanical steering mechanism comprises, for example, polygon mirror (s), oscillating mirror(s), rotating prism(s), rotating tilt mirror surface(s), single-plane or multi-plane mirror(s), or a combination thereof. In some embodiments, steering mechanism **340** may include non-mechanical steering mechanism (s) such as solid-state steering mechanism(s). For example, steering mechanism **340** can be based on tuning wavelength of the laser light combined with refraction effect, and/or based on reconfigurable grating/phase array. In some embodiments, steering mechanism **340** can use a single scanning device to achieve two-dimensional scanning or multiple scanning devices combined to realize two-dimensional scanning.

[0077] As another example, to implement steering mechanism **340**, a one-dimensional mechanical scanner can be used with an array or a large number of single-point transceivers. Specifically, the transceiver array can be mounted on a rotating platform to achieve 360-degree horizontal field of view. Alternatively, a static transceiver array can be combined with the one-dimensional mechanical scanner. A one-dimensional mechanical scanner comprises polygon mirror(s), oscillating mirror(s), rotating prism(s), rotating tilt mirror surface(s), or a combination thereof, for obtaining a forward-looking horizontal field of view. Steering mechanisms using mechanical scanners can provide robustness and reliability in high volume production for automotive applications.

[0078] As another example, to implement steering mechanism **340**, a two-dimensional transceiver can be used to generate a scan image or a 3D point cloud directly. In some embodiments, a stitching or micro shift method can be used to improve the resolution of the scan image or the field of view being scanned. For example, using a two-dimensional transceiver, signals generated at one direction (e.g., the horizontal direction) and signals generated at the other direction (e.g., the vertical direction) may be integrated, interleaved, and/or matched to generate a higher or full resolution image or 3D point cloud representing the scanned FOV.

[0079] Some implementations of steering mechanism **340** comprise one or more optical redirection elements (e.g., mirrors or lenses) that steer return light signals (e.g., by rotating, vibrating, or directing) along a receive path to direct the return light signals to optical receiver and light detector **330**. The optical redirection elements that direct light signals along the transmitting and receiving 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 transmitting and receiving paths are different although they may partially overlap (or in some cases, substantially overlap or completely overlap).

[0080] With reference still to FIG. **3**, LiDAR system **300** further comprises control circuitry **350**. Control circuitry **350** can be configured and/or programmed to control various parts of the LiDAR system **300** and/or to perform signal processing. In a typical system, control circuitry **350** can be configured and/or programmed to perform one or more control operations including, for example, controlling light source **310** to obtain the desired laser pulse timing, the pulse repetition rate, and power; controlling steering mechanism **340** (e.g., controlling the speed, direction, and/or other parameters) to scan the FOV and maintain pixel registration and/or alignment; controlling optical receiver and light detector **330** (e.g., controlling the sensitivity, noise reduction, filtering, and/or other parameters) such that it is an optimal state; and monitoring overall system health/status for functional safety (e.g., monitoring the laser output power and/or the steering mechanism operating status for safety).

[0081] Control circuitry **350** can also be configured and/or programmed to perform signal processing to the raw data generated by optical receiver and light detector **330** to derive distance and reflectance information, and perform data packaging and communication to vehicle perception and planning system **220** (shown in FIG. **2**). For example, control circuitry **350** determines the time it takes from transmitting a light pulse until a corresponding return light pulse is received; determines when a return light pulse is not received for a transmitted light pulse; determines the direction (e.g., horizontal and/or vertical information) for a transmitted/return light pulse; determines the estimated range in a particular direction; derives the reflectivity of an object in the FOV, and/or determines any other type of data relevant to LiDAR system **300**.

[0082] LiDAR system **300** can be disposed in a vehicle, which may operate in many different environments including hot or cold weather, rough road conditions that may cause intense vibration, high or low humidities, dusty areas, etc. Therefore, in some embodiments, optical and/or electronic components of LiDAR system **300** (e.g., optics in transmitter **320**, optical receiver and light detector **330**, and steering mechanism **340**) are disposed and/or configured in such a manner to maintain long term mechanical and optical stability. For example, components in LiDAR system **300** may be secured and sealed such that they can operate under all conditions a vehicle may encounter. As an example, an anti-moisture coating and/or hermetic sealing may be applied to optical components of transmitter **320**, optical receiver and light detector **330**, and steering mechanism **340** (and other components that are susceptible to moisture). As another example, housing(s), enclosure(s), fairing(s), and/or window can be used in LiDAR system **300** for providing desired characteristics such as hardness, ingress protection (IP) rating, self-cleaning capability, resistance to chemical and resistance to impact, or the like. In addition, efficient and economical methodologies for assembling LiDAR system **300** may be used to meet the LiDAR operating requirements while keeping the cost low.

[0083] It is understood by a person of ordinary skill in the art that FIG. **3** and the above descriptions are for illustrative purposes only, and a LiDAR system can include other functional units, blocks, or segments, and can include variations or combinations of these above functional units, blocks, or segments. For example, LiDAR system **300** can also include other components not depicted in FIG. **3**, 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 **310** and optical receiver and light detector **330** so that light detector **330** can accurately measure the time from when light source **310** transmits a light pulse until light detector **330** detects a return light pulse.

[0084] These components shown in FIG. **3** are coupled together using communications paths **312**, **314**, **322**, **332**, **342**, **352**, **362**, and **372**. 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, buses, 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 example LiDAR system, communication path **314** includes one or more optical fibers; communication path **352** represents an optical path; and communication paths **312**, **322**, **342**, and **362** are all electrical wires that carry electrical signals. The communication 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).

[0085] As described above, some LiDAR systems use the time-of-flight (ToF) of light signals (e.g., light pulses) to determine the distance to objects in a light path. For example, with reference to FIG. **5**A, an example LiDAR system **500** includes a laser light source (e.g., a fiber laser), a steering mechanism (e.g., a system of one or more moving mirrors), and a light detector (e.g., a photodetector with one or more optics). LiDAR system **500** can be implemented using, for example, LiDAR system **300** described above. LiDAR system **500** transmits a light pulse **502** along light path **504** as determined by the steering mechanism of LiDAR system **500**. In the depicted example, light pulse **502**, which is generated by the laser light source, is a short pulse of laser light. Further, the signal steering mechanism of the LiDAR system **500** is a pulsed-signal steering mechanism. However, it should be appreciated that LiDAR systems can operate by generating, transmitting, and detecting light signals that are not pulsed and derive ranges to an 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 pulsed signals also may be applicable to LiDAR systems that do not use one or both of these techniques.

[0086] Referring back to FIG. **5**A (e.g., illustrating a time-of-flight LiDAR system that uses light pulses), when light pulse **502** reaches object **506**, light pulse **502** scatters or reflects to form a return light pulse **508**. Return light pulse **508** may return to system **500** along light path **510**. The time from when transmitted light pulse **502** leaves LiDAR system **500** to when return light pulse **508** arrives back at LiDAR system **500** can be measured (e.g., by a processor or other electronics, such as control circuitry **350**, 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 **500** to the portion of object **506** where light pulse **502** scattered or reflected.

[0087] By directing many light pulses, as depicted in FIG. **5**B, LiDAR system **500** scans the external environment (e.g., by directing light pulses **502**, **522**, **526**, **530** along light paths **504**, **524**, **528**, **532**, respectively). As depicted in FIG. **5**C, LiDAR system **500** receives return light pulses **508**, **542**, **548** (which correspond to transmitted light pulses **502**, **522**, **530**, respectively). Return light pulses **508**, **542**, and **548** are formed by scattering or reflecting the transmitted light pulses by one of objects **506** and **514**. Return light pulses **508**, **542**, and **548** may return to LiDAR system **500** along light paths **510**, **544**, and **546**, respectively. Based on the direction of the transmitted light pulses (as determined by LiDAR system **500**) as well as the calculated range from LiDAR system **500** to the portion of objects that scatter or reflect the light pulses (e.g., the portions of objects **506** and **514**), the external environment within the detectable range (e.g., the field of view between path **504** and **532**, inclusively) can be precisely mapped or plotted (e.g., by generating a 3D point cloud or images).

[0088] If a corresponding light pulse is not received for a particular transmitted light pulse, then LiDAR system **500** may determine that there are no objects within a detectable range of LiDAR system **500** (e.g., an object is beyond the maximum scanning distance of LiDAR system **500**). For example, in FIG. **5**B, light pulse **526** may not have a corresponding return light pulse (as illustrated in FIG. **5**C) because light pulse **526** may not produce a scattering event along its transmission path **528** within the predetermined detection range. LiDAR system **500**, or an external system in communication with LiDAR system **500** (e.g., a cloud system or service), can interpret the lack of return light pulse as no object being disposed along light path **528** within the detectable range of LiDAR system **500**.

[0089] In FIG. **5**B, light pulses **502**, **522**, **526**, and **530** can be transmitted in any order, serially, in parallel, or based on other timings with respect to each other. Additionally, while FIG. **5**B depicts transmitted light pulses as being directed in one dimension or one plane (e.g., the plane of the paper), LiDAR system **500** can also direct transmitted light pulses along other dimension(s) or plane(s). For example, LiDAR system **500** can also direct transmitted light pulses in a dimension or plane that is perpendicular to the dimension or plane shown in FIG. **5**B, thereby forming a 2-dimensional transmission of the light pulses. This 2-dimensional transmission of the light pulses can be point-by-point, line-by-line, all at once, or in some other manner. That is, LiDAR system **500** can be configured to perform a point scan, a line scan, a one-shot without scanning, or a combination thereof. A point cloud or image from a 1-dimensional transmission of light pulses (e.g., a single horizontal line) can generate 2-dimensional data (e.g., (1) data from the horizontal transmission direction and (2) the range or distance to objects). Similarly, a point cloud or image from a 2-dimensional transmission of light pulses can generate 3-dimensional data (e.g., (1) data from the horizontal transmission direction, (2) data from the vertical transmission direction, and (3) the range or distance to objects). In general, a LiDAR system performing an n-dimensional transmission of light pulses generates (n+1) dimensional data. This is because the LiDAR system can measure the depth of an object or the range/distance to the object, which provides the extra dimension of data. Therefore, a 2D scanning by a LiDAR system can generate a 3D point cloud for mapping the external environment of the LiDAR system.

[0090] The density of a point cloud refers to the number of measurements (data points) per area performed by the LiDAR system. A point cloud density relates to the LiDAR scanning resolution. Typically, a larger point cloud density, and therefore a higher resolution, is desired at least for the region of interest (ROI). The density of points in a point cloud or image generated by a LiDAR system is equal to the number of pulses divided by the field of view. In some embodiments, the field of view can be fixed. Therefore, to increase the density of points generated by one set of transmission-receiving optics (or transceiver optics), the LiDAR system may need to generate a pulse more frequently. In other words, a light source in the LiDAR system may have a higher pulse repetition rate (PRR). On the other hand, by generating and transmitting pulses more frequently, the farthest distance that the LiDAR system can detect may be limited. For example, if a return signal from a distant 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, thereby causing ambiguity if the system cannot correctly correlate the return signals with the transmitted signals.

[0091] To illustrate, consider an example LiDAR system that can transmit laser pulses with a pulse 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 return pulses from consecutive pulses in a typical 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 return 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) may reduce the detection range of the system. Various techniques are used to mitigate the tradeoff between higher PRR and limited detection range. For example, multiple wavelengths can be used for detecting objects in different ranges. Optical and/or signal processing techniques (e.g., pulse encoding techniques) are also used to correlate between transmitted and return light signals.

[0092] Various systems, apparatus, and methods described herein may be implemented using digital circuitry, or using one or more computers using well-known computer processors, memory units, storage devices, computer software, and other components. Typically, a computer includes a processor for executing instructions and one or more memories for storing instructions and data. A computer may also include, or be coupled to, one or more mass storage devices, such as one or more magnetic disks, internal hard disks and removable disks, magneto-optical disks, optical disks, etc.

[0093] Various systems, apparatus, and methods described herein may be implemented using computers operating in a client-server relationship. Typically, in such a system, the client computers are located remotely from the server computers and interact via a network. The client-server relationship may be defined and controlled by computer programs running on the respective client and server computers. Examples of client computers can include desktop computers, workstations, portable computers, cellular smartphones, tablets, or other types of computing devices.

[0094] Various systems, apparatus, and methods described herein may be implemented using a computer program product tangibly embodied in an information carrier, e.g., in a non-transitory machine-readable storage device, for execution by a programmable processor; and the method processes and steps described herein, including one or more of the steps of at least some of the FIGS. **1-12**, may be implemented using one or more computer programs that are executable by such a processor. A computer program is a set of computer program instructions that can be used, directly or indirectly, in a computer to perform a certain activity or bring about a certain result. A computer program can be written in any form of programming language, including compiled or interpreted languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment.

[0095] A high-level block diagram of an example apparatus that may be used to implement systems, apparatus and methods described herein is illustrated in FIG. **6**. Apparatus **600** comprises a processor **610** operatively coupled to a persistent storage device **620** and a main memory device **630**. Processor **610** controls the overall operation of apparatus **600** by executing computer program instructions that define such operations. The computer program instructions may be stored in persistent storage device **620**, or other computer-readable medium, and loaded into main memory device **630** when execution of the computer program instructions is desired. For example, processor **610** may be used to implement one or more components and systems described herein, such as control circuitry **350** (shown in FIG. **3**), vehicle perception and planning system **220** (shown in FIG. **2**), and vehicle control system **280** (shown in FIG. **2**). Thus, the method steps of at least some of FIGS. **1-12** can be defined by the computer program instructions stored in main memory device **630** and/or persistent storage device **620** and controlled by processor **610** executing the computer program instructions. For example, the computer program instructions can be implemented as computer executable code programmed by one skilled in the art to perform an algorithm defined by the method steps discussed herein in connection with at least some of FIGS. **1-12**. Accordingly, by executing the computer program instructions, the processor **610** executes an algorithm defined by the method steps of these aforementioned figures. Apparatus **600** also includes one or more network interfaces **680** for communicating with other devices via a network. Apparatus **600** may also include one or more input/output devices **690** that enable user interaction with apparatus **600** (e.g., display, keyboard, mouse, speakers, buttons, etc.).

[0096] Processor **610** may include both general and special purpose microprocessors and may be the sole processor or one of multiple processors of apparatus **600**. Processor **610** may comprise one or more central processing units (CPUs), and one or more graphics processing units (GPUs), which, for example, may work separately from and/or multi-task with one or more CPUs to accelerate processing, e.g., for various image processing applications described herein. Processor **610**, persistent storage device **620**, and/or main memory device **630** may include, be supplemented by, or incorporated in, one or more application-specific integrated circuits (ASICs) and/or one or more field programmable gate arrays (FPGAs).

[0097] Persistent storage device **620** and main memory device **630** each comprise a tangible non-transitory computer readable storage medium. Persistent storage device **620**, and main memory device **630**, may each include high-speed random access memory, such as dynamic random access memory (DRAM), static random access memory (SRAM), double data rate synchronous dynamic random access memory (DDR RAM), or other random access solid state memory devices, and may include non-volatile memory, such as one or more magnetic disk storage devices such as internal hard disks and removable disks, magneto-optical disk storage devices, optical disk storage devices, flash memory devices, semiconductor memory devices, such as erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), compact disc read-only memory (CD-ROM), digital versatile disc read-only memory (DVD-ROM) disks, or other non-volatile solid state storage devices.

[0098] Input/output devices **690** may include peripherals, such as a printer, scanner, display screen, etc. For example, input/output devices **690** may include a display device such as a cathode ray tube (CRT), plasma or liquid crystal display (LCD) monitor for displaying information to a user, a keyboard, and a pointing device such as a mouse or a trackball by which the user can provide input to apparatus **600**.

[0099] Any or all of the functions of the systems and apparatuses discussed herein may be performed by processor **610**, and/or incorporated in, an apparatus or a system such as LiDAR system **300**. Further, LiDAR system **300** and/or apparatus **600** may utilize one or more neural networks or other deep-learning techniques performed by processor **610** or other systems or apparatuses discussed herein.

[0100] One skilled in the art will recognize that an implementation of an actual computer or computer system may have other structures and may contain other components as well, and that FIG. **6** is a high-level representation of some of the components of such a computer for illustrative purposes.

[0101] FIG. **7** is a diagram illustrating a side view of an exemplary LiDAR system **700** in accordance with various embodiments. A system for light ranging and detection (LiDAR) **700** comprises a laser transmitter **710** transmitting one or more channels of light pulses **715**. A rotating polygon mirror **720** has a plurality of reflective facets **725**. The rotating polygon mirror **720** directs the one or more channels of light pulses **715** from the laser transmitter **710** through a transmission region **760** at a top surface **750** of the system **700** toward an external field of view (FOV) and receives reflected light **745** from the external field of view illuminated by the one or more channels of light pulses **715**. A receiver **740** detects the reflected light **745** from channels corresponding to the one or more channels of light pulses **715**.

[0102] The laser transmitter **710**, the rotating polygon mirror **720**, and the receiver **740** are substantially coplanar on a plane parallel to the top surface. This configuration allows the LiDAR system **700** to have the transmitter **710**, the rotating polygon mirror **720**, and the receiver **740** not be stacked on top of each other in a direction perpendicular to the top surface **750**. Thus, the LiDAR system **700** has a thin profile or thickness (t) relative to conventional LiDAR system configurations where, e.g., transceivers or other components are stacked with a rotating polygon mirror. For example, the system may have a thickness of less than or equal to 30 millimeters in a direction perpendicular to the top surface. As mentioned above, most conventional LiDAR systems are bulky with at least 35 mm height, and they are designed to be mounted from the bottom so they can easily interfere with passenger space and cause other inconveniences if mounted behind a windshield or window. This configuration allows for the protrusion from a vehicle body (e.g., from behind a windshield or window) caused by conventionally mounted LiDAR systems to be minimized.

[0103] In an embodiment, the transmission region **760** may be an opening. For example, the opening **760** can eliminate the need for custom windows or windshields and significant design and maintenance such efforts require to implement LiDAR system **700**. Further, a vehicle windshield or window **730** mounting point may obviate the additional work is necessary to heat and clean a LiDAR window. Therefore, the opening **760** may be coupled to an interior surface of a vehicle window or windshield **730**. For example, an adhesive, a sealant, or other substance may be used to couple the opening **760** and/or another portion of the top surface **750** to the vehicle windshield or window **730**. Further, the vehicle windshield or window **730** may be configured to accommodate the transmission region **760**, or vice versa, e.g., to account for a particular windshield or window rake angle, a wavelength of the one or more channels of light pulses **715**, an operating specification, or other reasons. In addition, or alternatively, the transmission region **760** may be coaligned with an optically transparent region (e.g., with respect to the one or more channels of light pulses **715** and the reflected light **745**) in the vehicle window or windshield **730** such that the light pulses **715** can be transmitted, and the reflected light **745** can be received, through the vehicle window or windshield opening. In such cases, the transmission region **760** may be coupled to the optically transparent region in the vehicle window or windshield. For example, the transmission region **760** may include a LiDAR window (not shown) in some instances, and the vehicle windshield or window optically transparent region may be configured to accommodate the transmission region **760**, or vice versa, e.g., to account for a particular windshield or window rake angle, a wavelength of the one or more channels of light pulses **715**, an operating specification, or other reasons.

[0104] The rotating polygon mirror **720**, unlike many conventional LiDAR systems, may have an axis of rotation **726** that is substantially perpendicular to the top surface **750** due to the configuration of the rotating polygon mirror **720** on a plane parallel to the top surface. For example, the rotating polygon mirror **720** may rotate substantially parallel to the vehicle windshield or window **730**, which minimizes the thickness of the LiDAR system (and the protrusion into the vehicle interior) due to the rotating polygon mirror **720**. In some embodiments, the plurality of reflective facets **725** may have two or more different tilt angles to expand a vertical field of view. For example, the plurality of reflective facets **725** may have two or more different tilt angles to expand the vertical field of view, where the different tilt angles also account for a location of the opening **760** in the top surface **750**. The different tilt angles may also account for other factors, e.g., a material composition, a reflective quality of the vehicle windshield or window **730**, a rake angle of the windshield or window **730**, etc. In some embodiments, two or more of the plurality of reflective facets **725** may have tilt angles substantially similar to each other to form a region of interest (ROI) in the vertical field of view. For example, a larger point cloud density, and therefore a higher resolution, may be desired for the region of interest (ROI) in particular applications.

[0105] The transmitter **710** may include one or more Edge-Emitting Laser (EEL) or one or more Vertical-Cavity Surface-Emitting Laser (VCSEL). For example, transmitter **710** may comprise one or more VCSEL semiconductor laser diodes that emit light vertically from the surface of a chip, e.g., from a surface of a plane parallel to the top surface **750**. In addition, or alternatively, transmitter **710** may comprise one or more EEL diodes that emit light through the edge of a chip, e.g., from an edge of a plane parallel to the top surface **750**.

[0106] The receiver **740** may include one or more light detectors. For example, the one or more light detectors may be Silicon photomultipliers (SiPM) or Single Photon Avalanche Detectors (SPAD). The receiver **740** may also or alternatively comprise other light detector structures including, for example, an APD (avalanche photodiode) based structure, a PMT (photomultiplier tube) based structure, and/or quantum wires. Moreover, the receiver **740** may include many other detector structures and/or material systems, e.g., a narrow bandpass filter to remove light interference.

[0107] FIG. **8** is a diagram illustrating a bottom-up view of an exemplary LiDAR system **800** in accordance with various embodiments. Particularly, the bottom-up view shows the LiDAR system **800** from a perspective perpendicular to a plane parallel to a top surface of the system. Put another way, the bottom-up view shows the LiDAR system **800** underneath/behind an interior surface of a vehicle window or windshield, e.g., vehicle window or windshield **730**, from perspective generally perpendicular to the interior surface of the vehicle window or windshield.

[0108] FIG. **9** is a diagram illustrating a planar element **900** of an exemplary LiDAR system in accordance with various embodiments. Planar element **900** may have a width (w) sufficient to receive the laser transmitter **810**, the rotating polygon mirror **820**, and the receiver **840** such that they are substantially coplanar on the planar element **900** parallel to the top surface of the system **800**. For example, planar element **900** may comprise a printed circuit board having control circuitry (e.g., control circuitry **350** shown in FIG. **3**) so that components of the system **800**, e.g., the laser transmitter **810**, the rotating polygon mirror **820**, and the receiver **840**, can be controlled by or otherwise communicate with the control circuitry. The control circuitry may be configured and/or programmed to control various parts of the LiDAR system **800** and/or to perform signal processing, process raw data, etc. as described in FIG. **3** above. Planar element **900** may also include other components not shown, such as one or more power connectors, power supplies, and/or power lines.

[0109] In some embodiments, planar element **900** may comprise a cutout **910** configured to receive the rotating polygon mirror **820**, laser transmitter **810** and receiver **840** in a manner such that e.g., a bottom portion, top portion, or midpoint of the rotating polygon mirror **820** can be substantially coplanar with at least the laser transmitter **810** and receiver **840** on the planar element **900** parallel to the top surface of the system **800**. For example, the cutout **910** may be at back portion of the planar element **900** to better accommodate the substantially coplanar elements.

[0110] Referring back to FIG. **8**, a system for light ranging and detection (LiDAR) **800** comprises a laser transmitter **810** transmitting one or more channels of light pulses **815**. A rotating polygon mirror **820** has a plurality of reflective facets **825**. The rotating polygon mirror **820** directs the one or more channels of light pulses **815** from the laser transmitter **810** through a transmission region at a top surface of the system **800** toward an external field of view (FOV) and receives reflected light **845** from the external field of view illuminated by the one or more channels of light pulses **815**. Receiver **840** detects the reflected light **845** from channels corresponding to the one or more channels of light pulses **815**.

[0111] The laser transmitter **810**, the rotating polygon mirror **820**, and the receiver **840** are substantially coplanar on a plane parallel to the top surface. This configuration allows the LiDAR system **800** to have a thin profile, because the transmitter **810**, the rotating polygon mirror **820**, and the receiver **840** are not stacked on top of each other thickness-wise, i.e., in a direction perpendicular to the top surface.

[0112] In some embodiments, laser transmitter **810** may comprise one or more lenses to collimate the one or more channels of light pulses **815**. The one or more lenses may comprise one or more of a Fast-Axis Collimating (FAC) lens **891** or a Slow-Axis Collimating (SAC) lens **892**. For example, laser transmitter **810** may have an associated lens group comprising a FAC lens **891** and a SAC lens **892** (as shown), one or more FAC lenses **891**, one or more SAC lenses, etc. FAC lens **891** and SAC lens **892** may be configured to collect diverging laser beams from laser transmitter **810** and produce more parallel optical beams with reduced or minimum divergence. Moreover, FAC lens **891** and SAC lens **892** can be configured to achieve other desired properties such as a particular beam diameter, divergence, numerical aperture, focal length, or the like. The collimated optical beams can then be further directed through various optics such as other mirrors and/or lenses.

[0113] In some embodiments, the LiDAR system **800** may further comprise a prism reflector **880** reflecting the one or more channels of laser transmitter light pulses **815**, e.g., the collimated optical beams after being directed through FAC lens **891** and SAC lens **892**, toward the rotating polygon mirror **820**. For example, the prism reflector **880**, may be configured to reflect the one or more channels of laser transmitter light pulses **815** such that the coplanar configuration of the laser transmitter **810** and the rotating polygon mirror **820** can be achieved in a manner that further reduces a thickness of the LiDAR system **800** in a direction perpendicular to the top surface.

[0114] In some embodiments, the LiDAR system **800** may further comprise at least one of a collection lens **870**, a flat receiving mirror **860** collecting the reflected light **845** toward the receiver **840**. For example, the collection lens **870** may have asymmetric dimensions to bend the reflected light **845** into a direction that further reduces the thickness of the system **800** in a direction perpendicular to the top surface. Alternatively, instead of the collection lens **870** and the flat receiving mirror **860**, the LiDAR system **800** may comprise a curved focusing mirror (not shown) collecting the reflected light **845** toward the receiver **840**.

[0115] The transmitter **810** may include one or more Edge-Emitting Laser (EEL) or one or more Vertical-Cavity Surface-Emitting Laser (VCSEL). For example, transmitter **810** may comprise one or more VCSEL semiconductor laser diodes that emit light vertically from the surface of a chip, e.g., from a surface of a plane parallel to the top surface. In addition, or alternatively, transmitter **810** may comprise one or more EEL diodes that emit light through the edge of a chip, e.g., from an edge of a plane parallel to the top surface.

[0116] The receiver **840** may include one or more light detectors. For example, the one or more light detectors may be Silicon photomultipliers (SiPM) or Single Photon Avalanche Detectors (SPAD). The receiver **840** may also or alternatively comprise other light detector structures including, for example, an APD (avalanche photodiode) based structure, a PMT (photomultiplier tube) based structure, and/or quantum wires. Moreover, the receiver **840** may include many other detector structures (e.g., a detector board comprising the light detectors) and/or material systems, e.g., a narrow bandpass filter to remove light interference. It should be noted that each of the structures comprising receiver **840** may be substantially coplanar with the laser transmitter **810** and the rotating polygon mirror **820** on a plane parallel to the top surface.

[0117] FIGS. **10-11** are diagrams illustrating side views of various exemplary configurations of a LiDAR system in accordance with the various embodiments.

[0118] FIG. **10** is a diagram illustrating a side view of an exemplary LiDAR system **1000** having an off-center receiver element in accordance with various embodiments. In FIG. **10**, LiDAR system **1000** comprises a laser transmitter **1010** transmitting one or more channels of light pulses **1015**. A rotating polygon mirror **1020** has a plurality of reflective facets **1025**. The rotating polygon mirror **1020** directs the one or more channels of light pulses **1015** from the laser transmitter **1010** through a transmission region **1060** at a top surface **1050** of the system **1000** toward an external field of view (FOV) and receives reflected light **1045** from the external field of view illuminated by the one or more channels of light pulses **1015**. Receiver **1040** detects the reflected light **1045** from channels corresponding to the one or more channels of light pulses **1015**. The laser transmitter **1010**, the rotating polygon mirror **1020**, and the receiver **1040** are substantially coplanar on a plane parallel to the top surface **1050**, which can be substantially co-located with and/or coupled to an interior surface of a vehicle windshield or window **1030**.

[0119] In an embodiment, a collection lens **1070** may be off-set or off-center with respect to the reflected light **1045** to further reduce a thickness of the system **1000** in a direction perpendicular to the top surface **1050**. For example, LiDAR system **1000** may further comprise at least one collection lens **1070** and a flat receiving mirror (not shown) collecting the reflected light **1045** toward the receiver **1040**. In some embodiments, the collection lens **1070** may have asymmetric dimensions to bend the reflected light **1045** into a direction that further reduces the thickness of the system **1000** in a direction perpendicular to the top surface. For example, the collection lens **1070** may be configured to bend the reflected light **1045** by a higher or lesser degree toward the receiver **1040** based on its off-center or off-set orientation and/or its asymmetric dimensions. Thus, the collection lens **1070** may be off-set or off-center with respect to the reflected light **1045** while remaining substantially coplanar with the laser transmitter **1010**, the rotating polygon mirror **1020**, and the receiver **1040**. Alternatively, instead of the collection lens **1070** and the flat receiving mirror, the LiDAR system **1000** may comprise a curved focusing mirror (not shown) collecting the reflected light **1045** toward the receiver **1040**.

[0120] FIG. **11** is a diagram illustrating a side view of an exemplary LiDAR system **1100** in accordance with various embodiments. In FIG. **11**, LiDAR system **1100** comprises a laser transmitter **1110** transmitting one or more channels of light pulses **1115**. A rotating polygon mirror **1120** has a plurality of reflective facets **1125**. The rotating polygon mirror **1120** directs the one or more channels of light pulses **1115** from the laser transmitter **1110** through a transmission region **1160** at a top surface **1150** of the system **1100** toward an external field of view (FOV) and receives reflected light **1145** from the external field of view illuminated by the one or more channels of light pulses **1115**. Receiver **1140** detects the reflected light **1145** from channels corresponding to the one or more channels of light pulses **1115**. The laser transmitter **1110**, the rotating polygon mirror **1120**, and the receiver **1140** are substantially coplanar on a plane parallel to the top surface **1150**, which can be substantially co-located with and/or coupled to an interior surface of a vehicle windshield or window **1130**.

[0121] LiDAR system **1100** may further comprise at least one collection lens **1170** and a flat receiving mirror (not shown) collecting the reflected light **1145** toward the receiver **1040**. In FIG. **11**, a symmetrical and/or centered collection lens **1170** bends the reflected light **1145** toward the receiver **1140**. For example, the collection lens **1170** may be substantially coplanar with the laser transmitter **1110**, the rotating polygon mirror **1120**, and the receiver **1140**. Alternatively, instead of the collection lens **1170** and the flat receiving mirror, the LiDAR system **1100** may comprise a curved focusing mirror (not shown) collecting the reflected light **1145** toward the receiver **1140**.

[0122] In an alternative to an off-set or off-center collection lens **1170** as in FIG. **10** above, LiDAR system **1100** may further comprise a wedge-shaped prism **1180** to bend the reflected light **1145** into a direction that further reduces a thickness of the system in a direction perpendicular to the top surface. The wedge-shaped prism **1180** may be used in combination with the symmetrical and/or centered collection lens **1170** to bend the reflected light **1145** toward the receiver **1140**. For example, the wedge-shaped prism **1180** may be configured to bend the reflected light **1145** by a higher or lesser degree toward the receiver **1140** based on its orientation, thickness, angular dimensions, and/or other dimensions.

[0123] FIG. **12** is a flow diagram for a process **1200** of using a light ranging and detection (LiDAR) system in accordance with various embodiments. Process **1200** may be implemented by a LiDAR system comprising a laser transmitter, a rotating polygon mirror having a plurality of reflective facets, and a receiver. Starting at step **1210**, the laser transmitter transmits one or more channels of light pulses. At step **1220**, the rotating polygon mirror having the plurality of reflective facets directs the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the LiDAR system toward an external field of view and receives reflected light from the external field of view illuminated by the one or more channels of light pulses. At step **1230**, the receiver detects the reflected light from channels corresponding to the one or more channels of light pulses, where the laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface.

[0124] It should be understood that the steps in FIG. **12** are merely illustrative and that additional steps may be added, and the order of the steps may be rearranged.

[0125] Additional embodiments are included below.

[0126] (1) A system for light ranging and detection (LiDAR), comprising:

[0127] a laser transmitter transmitting one or more channels of light pulses;

[0128] a rotating polygon mirror having a plurality of reflective facets, wherein the rotating polygon mirror directs the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the system toward an external field of view and receives reflected light from the external field of view illuminated by the one or more channels of light pulses; and

[0129] a receiver detecting the reflected light from channels corresponding to the one or more channels of light pulses,

[0130] wherein the laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface.

[0131] (2) The system of (1), wherein the system has a thickness of less than or equal to 30 millimeters in a direction perpendicular to the top surface.

[0132] (3) The system of any of (1)-(2), wherein the transmission region is an opening.

[0133] (4) The system of (3), wherein the opening is coupled to an interior surface of a vehicle window or windshield.

[0134] (5) The system of any of (1)-(4), wherein the transmission region is coaligned with an optically transparent region in a vehicle window or windshield.

[0135] (6) The system of (5), wherein the transmission region is coupled to the optically transparent region in the vehicle window or windshield.

[0136] (7) The system of any of (1)-(6), wherein the rotating polygon mirror axis of rotation is substantially perpendicular to the top surface.

[0137] (8) The system of any of (1)-(7), wherein the plurality of reflective facets has two or more different tilt angles to expand a vertical field of view.

[0138] (9) The system of (8), wherein two or more of the plurality of reflective facets have tilt angles substantially similar to each other to form a region of interest (ROI) in the vertical field of view.

[0139] (10) The system of any of (1)-(9), further comprising one or more lenses collimating the one or more channels of light pulses from the laser transmitter.

[0140] (11) The system of (10), wherein the one or more lenses comprise one or more of the following: a Fast-Axis Collimating (FAC) lens or a Slow-Axis Collimating (SAC) lens.

[0141] (12) The system of any of (1)-(11), further comprising a prism reflector reflecting the one or more channels of laser transmitter light pulses toward the rotating polygon mirror.

[0142] (13) The system of any of (1)-(12), further comprising at least one of a collection lens, a flat receiving mirror, or a curved focusing mirror collecting the reflected light toward the receiver.

[0143] (14) The system of any of (1)-(13), further comprising a collection lens with asymmetric dimensions to bend the reflected light into a direction that further reduces a thickness of the system in a direction perpendicular to the top surface.

[0144] (15) The system of any of (1)-(14), further comprising a wedge-shaped prism to bend the reflected light into a direction that further reduces a thickness of the system in a direction perpendicular to the top surface.

[0145] (16) The system of any of (1)-(15), wherein the laser transmitter comprises one or more of the following: an Edge-Emitting Laser (EEL) or a Vertical-Cavity Surface-Emitting Laser (VCSEL).

[0146] (17) The system of any of (1)-(16), wherein the receiver comprises one or more light detectors.

[0147] (18) The system of (17), wherein the one or more light detectors comprise one or more of the following: a Silicon photomultiplier (SiPM) or a Single Photon Avalanche Detector (SPAD).

[0148] (19) The system of any of (1)-(18), wherein the receiver comprises a narrow bandpass filter to remove light interference.

[0149] (20) A vehicle comprising the system of any of (1)-(19).

[0150] (21) The vehicle of (20), further comprising a window or windshield, wherein the transmission region is an opening coupled to an interior surface of the vehicle window or windshield.

[0151] (22) The vehicle any of (20)-(21), further comprising a window or windshield, wherein the transmission region is coaligned with an optically transparent region in the vehicle window or windshield.

[0152] (23) The vehicle of (22), wherein the transmission region is coupled to the optically transparent region in the vehicle window or windshield.

[0153] (24) A method of using a light ranging and detection (LiDAR) system comprising a laser transmitter, a rotating polygon mirror having a plurality of reflective facets, and a receiver, the method comprising:

[0154] transmitting, by the laser transmitter, one or more channels of light pulses;

[0155] directing, by the rotating polygon mirror having the plurality of reflective facets, the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the LiDAR system toward an external field of view and receiving reflected light from the external field of view illuminated by the one or more channels of light pulses; and

[0156] detecting, by the receiver, the reflected light from channels corresponding to the one or more channels of light pulses,

[0157] wherein the laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface.

[0158] The foregoing specification is to be understood as being in every respect illustrative and exemplary, but not restrictive, and the scope of the invention disclosed herein is not to be determined from the specification, but rather from the claims as interpreted according to the full breadth permitted by the patent laws. It is to be understood that the embodiments shown and described herein are only illustrative of the principles of the present invention and that various modifications may be implemented by those skilled in the art without departing from the scope and spirit of the invention. Those skilled in the art could implement various other feature combinations without departing from the scope and spirit of the invention.

What is claimed is:

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

a laser transmitter transmitting one or more channels of light pulses;

a rotating polygon mirror having a plurality of reflective facets, wherein the rotating polygon mirror directs the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the system toward an external field of view and receives reflected light from the external field of view illuminated by the one or more channels of light pulses; and

a receiver detecting the reflected light from channels corresponding to the one or more channels of light pulses,

wherein the laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface.

2. The system of claim **1**, wherein the system has a thickness of less than or equal to 30 millimeters in a direction perpendicular to the top surface.

3. The system of claim **1**, wherein the transmission region is an opening.

4. The system of claim **3**, wherein the opening is coupled to an interior surface of a vehicle window or windshield.

5. The system of claim **1**, wherein the transmission region is coaligned with an optically transparent region in a vehicle window or windshield.

6. The system of claim **5**, wherein the transmission region is coupled to the optically transparent region in the vehicle window or windshield.

7. The system of claim **1**, wherein the rotating polygon mirror axis of rotation is substantially perpendicular to the top surface.

8. The system of claim **1**, wherein the plurality of reflective facets has two or more different tilt angles to expand a vertical field of view.

9. The system of claim **8**, wherein two or more of the plurality of reflective facets have tilt angles substantially similar to each other to form a region of interest (ROI) in the vertical field of view.

10. The system of claim **1**, further comprising one or more lenses collimating the one or more channels of light pulses from the laser transmitter.

11. The system of claim **10**, wherein the one or more lenses comprise one or more of the following: a Fast-Axis Collimating (FAC) lens or a Slow-Axis Collimating (SAC) lens.

12. The system of claim **1**, further comprising a prism reflector reflecting the one or more channels of laser transmitter light pulses toward the rotating polygon mirror.

13. The system of claim **1**, further comprising at least one of a collection lens, a flat receiving mirror, or a curved focusing mirror collecting the reflected light toward the receiver.

14. The system of claim **1**, further comprising a collection lens with asymmetric dimensions to bend the reflected light into a direction that further reduces a thickness of the system in a direction perpendicular to the top surface.

15. The system of claim **1**, further comprising a wedge-shaped prism to bend the reflected light into a direction that further reduces a thickness of the system in a direction perpendicular to the top surface.

16. The system of claim **1**, wherein the laser transmitter comprises one or more of the following: an Edge-Emitting Laser (EEL) or a Vertical-Cavity Surface-Emitting Laser (VCSEL).

17. The system of claim **1**, wherein the receiver comprises one or more light detectors.

18. The system of claim **17**, wherein the one or more light detectors comprise one or more of the following: a Silicon photomultiplier (SiPM) or a Single Photon Avalanche Detector (SPAD).

19. The system of claim **1**, wherein the receiver comprises a narrow bandpass filter to remove light interference.

20. A vehicle comprising:

system for light ranging and detection (LiDAR), comprising:

a laser transmitter transmitting one or more channels of light pulses;

a rotating polygon mirror having a plurality of reflective facets, wherein the rotating polygon mirror directs the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the system toward an external field of view and receives reflected light from the external field of view illuminated by the one or more channels of light pulses; and

a receiver detecting the reflected light from channels corresponding to the one or more channels of light pulses, wherein the laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface.

21. The vehicle of claim **20**, further comprising a window or windshield, wherein the transmission region is an opening coupled to an interior surface of the vehicle window or windshield.

22. The vehicle of claim **20**, further comprising a window or windshield, wherein the transmission region is coaligned with an optically transparent region in the vehicle window or windshield.

23. The vehicle of claim **22**, wherein the transmission region is coupled to the optically transparent region in the vehicle window or windshield.

24. A method of using a light ranging and detection (LiDAR) system comprising a laser transmitter, a rotating polygon mirror having a plurality of reflective facets, and a receiver, the method comprising:

transmitting, by the laser transmitter, one or more channels of light pulses;

directing, by the rotating polygon mirror having the plurality of reflective facets, the one or more channels of light pulses from the laser transmitter through a transmission region at a top surface of the LiDAR system toward an external field of view and receiving reflected light from the external field of view illuminated by the one or more channels of light pulses; and

detecting, by the receiver, the reflected light from channels corresponding to the one or more channels of light pulses,

wherein the laser transmitter, the rotating polygon mirror, and the receiver are substantially coplanar on a plane parallel to the top surface.

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