

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property
Organization

International Bureau

(43) International Publication Date
06 June 2019 (06.06.2019)



(10) International Publication Number

WO 2019/108752 A2

(51) International Patent Classification:

G01S 17/89 (2006.01)

(21) International Application Number:

PCT/US2018/062994

(22) International Filing Date:

29 November 2018 (29.11.2018)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/593,105	30 November 2017 (30.11.2017)	US
16/203,422	28 November 2018 (28.11.2018)	US
16/203,430	28 November 2018 (28.11.2018)	US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

(54) Title: OPTICAL DESIGNS AND DETECTOR DESIGNS FOR IMPROVED RESOLUTION IN LIDAR SYSTEMS

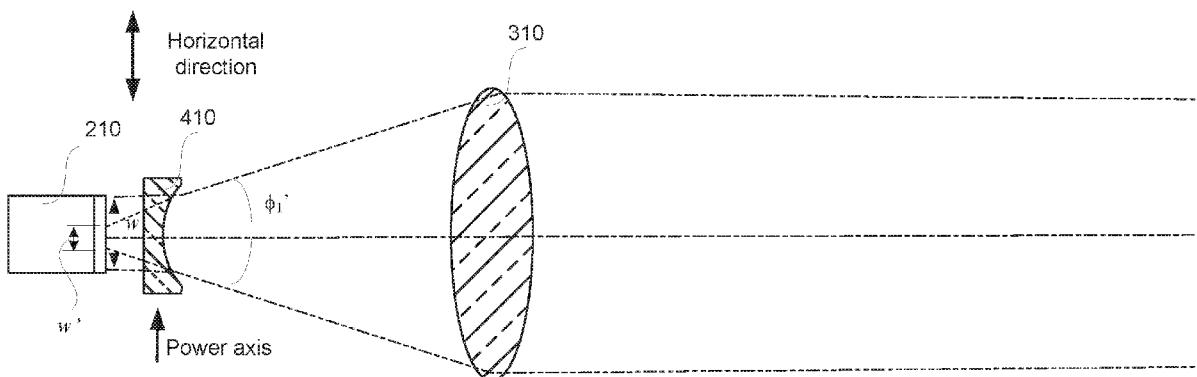


FIG. 4A

(57) Abstract: An optical system includes a laser source having an emission area that has a first width in a first direction and a first height in a second direction orthogonal to the first direction, the first width being greater than the first height. The optical system further includes a cylindrical lens having a negative power and positioned in front of the laser source. The cylindrical lens is oriented such that a power axis of the cylindrical lens is along the first direction. The cylindrical lens is configured to transform the emission area of a laser beam emitted by the laser source into a virtual emission area having a virtual width and a virtual height, where the virtual width is less than the first width. The optical system further includes an rotationally symmetric lens positioned downstream from the cylindrical lens and configured to collimate and direct the laser beam towards a far-field.

Published:

- *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

OPTICAL DESIGNS AND DETECTOR DESIGNS FOR IMPROVED 5 RESOLUTION IN LIDAR SYSTEMS

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This PCT application claims the benefit of U.S. Provisional Patent Application No. 62/593,105, filed on November 30, 2017, and priority to U.S. Patent Application No. 10 16/203,422, entitled “OPTICAL DESIGNS USING CYLINDRICAL LENSES FOR IMPROVED RESOLUTION IN LIDAR SYSTEMS,” filed on November 28, 2018, and U.S. Patent Application No. 16/203,430, entitled “DETECTOR DESIGNS FOR IMPROVED RESOLUTION IN LIDAR SYSTEMS,” filed on November 28, 2018, the contents of which are hereby incorporated by reference in its entirety.

15

BACKGROUND OF THE INVENTION

[0002] Three-dimensional sensors can be applied in autonomous vehicles, drones, robotics, security applications, and the like. Scanning lidar sensors may achieve good angular resolutions appropriate for such applications at an affordable cost. However, lidar systems 20 and methods with even better resolutions are needed.

SUMMARY OF THE INVENTION

[0003] According to some embodiments, an optical system includes a laser source having an emission area that has a first width in a first direction and a first height in a second 25 direction orthogonal to the first direction. The first width is greater than the first height. The optical system further includes a cylindrical lens having a negative power and positioned in front of the laser source. The cylindrical lens is oriented such that a power axis of the cylindrical lens is substantially along the first direction. The cylindrical lens is configured to transform the emission area of a laser beam emitted by the laser source into a virtual emission 30 area having a virtual width and a virtual height, where the virtual width is less than the first width of the emission area of the laser source. The optical system further includes an rotationally symmetric lens positioned downstream from the cylindrical lens. The

rotationally symmetric lens is configured to collimate and direct the laser beam towards a far-field.

[0004] According to some embodiments, a lidar system includes a laser source configured to emit a plurality of laser pulses. The laser source has an emission area that has a first width in a first direction and a first height in a second direction orthogonal to the first direction.

5 The first width is greater than the first height. The lidar system further includes a cylindrical lens having a negative power and positioned in front of the laser source. The cylindrical lens is oriented such that a power axis of the cylindrical lens is substantially along the first direction. The cylindrical lens is configured to transform the emission area into a virtual

10 emission area having a virtual width and a virtual height, where the virtual width is less than the first width. The lidar system further includes an emission lens positioned downstream from the cylindrical lens. The emission lens is rotationally symmetric and is configured to collimate and direct the plurality of laser pulses towards one or more objects. The one or more objects may reflect the plurality of laser pulses to generate a plurality of return laser

15 pulses. The lidar system further includes a receiving lens. The receiving lens is rotationally symmetric and is configured to receive and focus each of the plurality of return laser pulses to a return beam spot at a focal plane of the receiving lens. The lidar system further includes a detector. The detector has a detection surface positioned at the focal plane of the receiving lens, and is configured to receive and detect each of the plurality of return laser pulses. The

20 lidar system further includes a processor coupled to the laser source and the detector. The processor is configured to determine a time of flight for each of the plurality of return laser pulses, and construct a three-dimensional image of the one or more objects based on the determined time of flight for each of the plurality of return laser pulses.

[0005] According to some embodiments, a method of three-dimensional imaging includes translating a laser source and a cylindrical lens in unison. The laser source is translated to each of a plurality of emission locations in an emission plane. The laser source has an emission area with a first height and a first width greater than the first height. The cylindrical lens has a negative power and positioned in front of the laser source. The cylindrical lens is oriented such that a power axis of the cylindrical lens is substantially in a width direction.

30 The method further includes emitting, using the laser source, a plurality of laser pulses. Each of the plurality of laser pulses is emitted at a respective one of the plurality of emission locations. The method further includes collimating and directing, using an emission lens, the plurality of laser pulses towards one or more objects. The one or more objects may reflect

each of the plurality of laser pulses to generate a plurality of return laser pulses. The method further includes receiving and focusing, using a receiving lens, each of the plurality of return laser pulses to a plurality of corresponding detection locations in a detection plane. Each corresponding detection location is conjugate with a respective emission location. The 5 method further includes translating a detector to each of the plurality of corresponding detection locations in the detection plane, and detecting, using the detector, each respective return laser pulse of the plurality of return laser pulses at each respective detection location of the plurality of detection locations. The method further includes determining, using a processor, a time of flight for each of the plurality of return laser pulses, and constructing, 10 using the processor, a three-dimensional image of the one or more objects based on the time of flight for each of the plurality of return laser pulses.

[0006] According to some embodiments, a lidar system includes a laser source configured to emit a laser beam carrying an electromagnetic signal, and an emission lens configured to collimate and direct the laser beam towards one or more objects within a field of view of the 15 laser beam. The one or more objects may reflect the laser beam to generate a return laser beam. The lidar system further includes a receiving lens configured to receive and focus the return laser beam to a return beam spot at a focal plane of the receiving lens, and a detector. The detector includes a plurality of photo sensors arranged as an array at the focal plane of the receiving lens. Each respective photo sensor has a respective sensing area and is 20 configured to receive and detect a respective portion of the return laser beam corresponding to a respective section of the field of view of the laser beam. The lidar system further includes a processor coupled to the laser source and the detector. The processor is configured to determine a respective time of flight for each respective portion of the return laser beam detected at the respective photo sensor of the detector, and construct a three-dimensional 25 image of the one or more objects based on the respective time of flight for each respective portion of the return laser beam.

[0007] According to some embodiments, a method of three-dimensional imaging includes emitting, using a laser source, a laser pulse, and collimating and directing, using an emission lens, the laser pulse towards one or more objects within a field of view of the laser pulse. 30 The one or more objects may reflect the laser pulse to generate a return laser pulse. The method further includes receiving and focusing, using a receiving lens, the return laser pulse to a return beam spot at a focal plane of the receiving lens. The method further includes detecting, using a detector that includes a plurality of photo sensors arranged as an array at

the focal plane of the receiving lens, a respective portion of the return laser pulse received at each respective photo sensor. The respective portion of the return laser pulse corresponds to a respective section of the field of view of the laser pulse. The method further includes, using a processor coupled to the laser source and the detector, determining a time of flight for each 5 respective portion of the return laser pulse, and constructing a three-dimensional image of the one or more objects based on the time of flight for each respective portion of the return laser pulse.

[0008] According to some embodiments, a lidar system includes a laser source configured to emit a laser beam carrying an electromagnetic signal, a lens configured to collimate and 10 direct the laser beam towards one or more objects within a field of view of the laser beam. The one or more objects may reflect the laser beam to generate a return laser beam. The lens is further configured to receive and focus the return laser beam to a return beam spot at a focal plane of the lens. The lidar system further includes a detector. The detector includes a plurality of photo sensors arranged as an array at the focal plane of the lens. Each respective 15 photo sensor has a respective sensing area and is configured to receive and detect a respective portion of the return laser beam corresponding to a respective section of the field of view of the laser beam. The lidar system further includes a processor coupled to the laser source and the detector. The processor is configured to determine a respective time of flight for each respective portion of the return laser beam detected at the respective photo sensor of the 20 detector, and construct a three-dimensional image of the one or more objects based on the respective time of flight for each respective portion of the return laser beam.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1 illustrates schematically a lidar sensor for three-dimensional imaging 25 according to some embodiments of the present invention.

[0010] FIG. 2 illustrates schematically a laser source that has an elongated emission area and different divergence angles in the horizontal and vertical directions.

[0011] FIGS. 3A and 3B illustrate schematically an optical system for collimating a laser beam in a lidar system.

[0012] FIGS. 4A – 4B illustrate schematically an optical system for collimating a laser beam in a lidar system according to some embodiments of the present invention.

[0013] FIGS. 5A – 5D illustrate schematically an effect of a cylindrical lens on the far-field beam spot shape according to some embodiments of the present invention.

[0014] FIG. 6A illustrates schematically an exemplary configuration of a laser source and a cylindrical lens that may be used in a lidar system according to some embodiments of the present invention.

[0015] FIG. 6B illustrates schematically another exemplary configuration of a laser source and a cylindrical lens according to some embodiments of the present invention.

[0016] FIG. 7A illustrates a cross-sectional view of an optical system for collimating a laser beam in a lidar system according to some embodiments of the present invention.

[0017] FIG. 7B illustrates a cross-sectional view of an optical system for collimating laser beams in a lidar system that includes two laser sources according to some embodiments of the present invention.

[0018] FIG. 8 shows a simplified flowchart illustrating a method of three-dimensional imaging using a lidar system according to some embodiments of the present invention.

[0019] FIG. 9 illustrates schematically a lidar system according to some embodiments of the present invention.

[0020] FIG. 10A illustrates a detector configuration according to some embodiments of the present invention.

[0021] FIG. 10B illustrates a detector that includes a single photo sensor.

[0022] FIGS. 11A – 11C illustrate schematically timing diagrams of laser pulses for the example illustrated in FIGS. 9 and 10 according to some embodiments of the present invention.

[0023] FIG. 12A shows a schematic plan view of a detector according to some embodiments of the present invention.

[0024] FIG. 12B shows a schematic plan view of a detector according to some embodiments of the present invention.

[0025] FIG. 13 illustrates schematically a lidar system according to some embodiments of the present invention.

[0026] FIG. 14 shows a simplified flowchart illustrating a method of three-dimensional imaging using a lidar system according to some embodiments of the present invention.

DETAILED DESCRIPTION OF THE SPECIFIC EMBODIMENTS

5 **[0027]** The present invention relates generally to lidar systems and methods for three-dimensional imaging. More specifically, the present invention relates to optical and detector designs and methods for improved resolutions in lidar systems. Merely by way of example, embodiments of the present invention provide an optical system for projecting a laser beam emitted by a laser source that has an asymmetric emission area and asymmetric divergence 10 angles. The optical system may include a cylindrical lens with a negative power (e.g., a plano-concave cylindrical lens) placed in front of the laser source. The cylindrical lens may be configured to transform the emission area of the laser source into a virtual emission area that is substantially symmetric and smaller than the physical emission area. In combination with a rotationally symmetric projecting lens (e.g., a spherical lens), a symmetric far-field 15 beam spot (or return beam spot) may be achieved that is smaller than would be achieved without the cylindrical lens. Since the resolution of a lidar system may depend on the far-field beam spot size, such an optical system may improve the resolution of the lidar system. Embodiments of the present invention also provide a detector that includes an array of photo 20 sensors. Each photo sensor in the array may be configured to receive and detect a portion of a return laser beam. A lidar system with such a detector may afford enhanced resolutions as compared to a detector with a single photo sensor.

25 **[0028]** FIG. 1 illustrates schematically a lidar sensor 100 for three-dimensional imaging according to some embodiments of the present invention. The lidar sensor 100 includes an emitting lens 130 and a receiving lens 140. The lidar sensor 100 includes a laser source 110a disposed substantially in a back focal plane of the emitting lens 130. The laser source 110a is operative to emit a laser pulse 120 from a respective emission location in the back focal plane 30 of the emitting lens 130. The emitting lens 130 is configured to collimate and direct the laser pulse 120 toward an object 150 located in front of the lidar sensor 100. For a given emission location of the laser source 110a, the collimated laser pulse 120' is directed at a corresponding angle toward the object 150.

[0029] The laser pulse 120 may be reflected off of the object 150, thereby generating a return laser pulse 122 directed toward the receiving lens 140. The receiving lens 140 is configured to focus the return laser pulse 122 onto a corresponding detection location in the

focal plane of the receiving lens 140. The lidar sensor 100 further includes a detector 160a disposed substantially at the focal plane of the receiving lens 140. The detector 160a is configured to receive and detect the return laser pulse 122 at the corresponding detection location. The corresponding detection location of the detector 160a is conjugate with the 5 respective emission location of the laser source 110a.

[0030] The laser pulse 120 may be of a short duration, for example, 100 ns pulse width. The lidar sensor 100 further includes a processor 190 coupled to the laser source 110a and the detector 160a. The processor 190 is configured to determine a time of flight (TOF) of the return laser pulse 122. Since the return laser pulse 122 travels at the speed of light, a distance 10 between the lidar sensor 100 and the object 150 may be determined based on the determined time of flight.

[0031] According to some embodiments, the emission lens 130 and the receiving lens 140 may be fixed. The laser source 110a may be raster scanned to a plurality of emission locations in the back focal plane of the emitting lens 130, and is configured to emit a plurality 15 of laser pulses at the plurality of emission locations. Each laser pulse emitted at a respective emission location is collimated by the emitting lens 130 and directed at a respective angle toward the object 150, and incents at a corresponding point on the surface of the object 150. Thus, as the laser source 110a is raster scanned within a certain area in the back focal plane of the emitting lens 130, a corresponding object area on the object 150 is scanned. The 20 detector 160a is raster scanned to a plurality of corresponding detection locations in the focal plane of the receiving lens 140. The scanning of the detector 160a is performed synchronously with the scanning of the laser source 110a, so that the detector 160a and the laser source 110a are always conjugate with each other at any given time.

[0032] By determining the time of flight for each laser pulse emitted at a respective 25 emission location, the distance from the lidar sensor 100 to each corresponding point on the surface of the object 150 may be determined. In some embodiments, the processor 190 is coupled with a position encoder that detects the position of the laser source 110a at each emission location. Based on the emission location, the angle of the collimated laser pulse 120' may be determined. The X-Y coordinate of the corresponding point on the surface of 30 the object 150 may be determined based on the angle and the distance to the lidar sensor 100. Thus, a three-dimensional image of the object 150 may be constructed based on the measured distances from the lidar sensor 100 to various points on the surface of the object 150. In

some embodiments, the three-dimensional image may be represented as a point cloud, i.e., a set of X, Y, and Z coordinates of the points on the surface of the object 150.

[0033] In alternative embodiments, the laser source 110a and the detector 160a may be fixed. The emission lens 130 may be scanned relative to the laser source 110a, and the receiving lens 140 may be scanned relative to the detector 160a synchronously with the scanning of the emission lens 130. In some further embodiments, the laser source 110a and the detector 160a may be scanned in at least a first direction, while the emission lens 130 and the receiving lens 140 are scanned in at least a second direction. For example, the laser source 110a and the detector 160a may be scanned in the horizontal direction, while the emission lens 130 and the receiving lens 140 are scanned in the vertical direction. In some embodiments, the laser source 110a and the detector 160a are scanned in two directions, while the emission lens 130 and the receiving lens 140 are also scanned in two directions. In some embodiments, the laser source 110a and the detector 160a may be scanned in two directions in a Lissajous pattern. The emission lens 130 and the receiving lens 140 may also be scanned in two directions in a Lissajous pattern.

[0034] In some embodiments, the laser source 110a may be configured to emit a frequency-modulated continuous-wave (FMCW) laser beam, and the processor 190 may be configured to determine the distance between the object 150 and the lidar sensor 100 by demodulating a return laser beam.

[0035] In some embodiments, the emission lens 130 and the receiving lens 140 may comprise the same lens; that is, a single lens may be configured to collimate and direct the laser pulse 120 emitted by the laser source 110a toward the object 150, as well as to focus the return laser pulse 122 onto the detector 160a.

[0036] In some embodiments, the intensity of the return laser pulse is measured and used to adjust the power of subsequent laser pulses from the same emission point, in order to prevent saturation of the detector, improve eye-safety, or reduce overall power consumption. The power of the laser pulse may be varied by varying the duration of the laser pulse, the voltage or current applied to the laser, or the charge stored in a capacitor used to power the laser. In the latter case, the charge stored in the capacitor may be varied by varying the charging time, charging voltage, or charging current to the capacitor. In some embodiments, the intensity may also be used to add another dimension to the image. For example, the image may contain X, Y, and Z coordinates, as well as reflectivity (or brightness).

[0037] The angular field of view (AFOV) of the lidar sensor 100 may be estimated based on the scanning range of the laser source 110a and the focal length of the emitting lens 130 as,

$$AFOV = 2 \tan^{-1}\left(\frac{h}{2f}\right),$$

5 where h is scan range of the laser source 110a along certain direction, and f is the focal length of the emitting lens 130. For a given scan range h , shorter focal lengths would produce wider AFOVs. For a given focal length f , larger scan ranges would produce wider AFOVs.

[0038] In some embodiments, the lidar sensor 100 may include multiple laser sources disposed as an array at the back focal plane of the emitting lens 130, so that a larger total 10 AFOV may be achieved while keeping the scan range of each individual laser source relatively small. Accordingly, the lidar sensor 100 may include multiple detectors disposed as an array at the focal plane of the receiving lens 140, each detector being conjugate with a respective laser source. For example, the lidar sensor 100 may include a second laser source 110b and a second detector 160b, as illustrated in FIG. 1. In other embodiments, the lidar 15 sensor 100 may include four laser sources and four detectors, or eight laser sources and eight detectors. In one embodiment, the lidar sensor 100 may include 8 laser sources arranged as a 4×2 array and 8 detectors arranged as a 4×2 array, so that the lidar sensor 100 may have a wider AFOV in the horizontal direction than its AFOV in the vertical direction. According to various embodiments, the total AFOV of the lidar sensor 100 may range from about 5 20 degrees to about 15 degrees, or from about 15 degrees to about 45 degrees, or from about 45 degrees to about 90 degrees, depending on the focal length of the emitting lens, the scan range of each laser source, and the number of laser sources.

[0039] The laser source 110a may be configured to emit laser pulses in the ultraviolet, visible, or near infrared wavelength ranges. The energy of each laser pulse may be in the 25 order of microjoules, which is normally considered to be eye-safe for repetition rates in the KHz range. For laser sources operating in wavelengths greater than about 1500 nm, the energy levels could be higher as the eye does not focus at those wavelengths. The detector 160a may comprise a silicon avalanche photo sensor, a photomultiplier, a PIN diode, or other semiconductor sensors.

30 **[0040]** Some laser sources, for example solid state lasers, may have an asymmetric emission area and an asymmetric beam profile in the near-field as well as in the far-field.

FIG. 2 illustrates schematically a laser source 210, for example, a semiconductor laser source, that has an elongated emission area 220. The emission area 220 may have a height h in the vertical direction, and a width w in the horizontal direction that is greater than the height h . For example, for a solid state laser used in a lidar system, the height h may be about 10 μm , 5 and the width w may be about 200 μm . Although the emission area 220 is illustrated as having a rectangular shape in FIG. 2, the emission area 220 may have a rectangular shape with rounded corners or an elliptical shape.

[0041] The laser beam emitted by such laser sources may also have different divergence angles in the horizontal and vertical directions. As illustrated in FIG. 2, the horizontal 10 emission fan 240 (e.g., in the tangential plane) may subtend an angle ϕ_1 (which may be referred herein as the angular divergence), and the vertical emission fan 230 (e.g., in the sagittal plane) may subtend an angle ϕ_2 that is greater than ϕ_1 . For example, the angular divergence ϕ_1 of the horizontal emission fan 240 may be about 10 degrees, and the angular divergence ϕ_2 of the vertical emission fan 230 may be about 25 degrees. In other words, the 15 light beam has a larger source dimension and smaller divergence in the horizontal direction, and a smaller source dimension and larger divergence in the vertical direction. Because the laser beam diverges faster in the vertical direction, the vertical direction may be referred to as the fast axis, and the horizontal direction may be referred to as the slow axis.

[0042] The asymmetric emission area and asymmetric angular divergence of a laser beam 20 as described above may make it more challenging to collimate the laser beam in both the horizontal and vertical directions using rotationally symmetric lenses, such as spherical lenses or aspherical lenses. FIGS. 3A and 3B illustrate schematically an optical system for collimating a laser beam in a lidar system. The optical system includes a spherical lens 310 positioned in front of the laser source 210 (the spherical lens 310 can be, e.g., the emission 25 lens 130 illustrated in FIG. 1). FIG. 3A illustrates the light paths for the horizontal emission fan; and FIG. 3B illustrates the light paths for the vertical emission fan.

[0043] As illustrated in FIG. 3B, if the emission surface of the laser source 210 is positioned at approximately the back focal plane of the lens 310, light rays in the vertical emission fan may be substantially collimated by the lens 310; that is, the light rays post the 30 lens 310 along the optical path may be nearly parallel to each other. On the other hand, as illustrated in FIG. 3A, light rays in the horizontal emission fan may be converging post the lens 310 along the optical path, as the power of the lens 310 may be too large for collimating

the horizontal emission fan, which has a smaller divergence angle ϕ_1 than the divergence angle ϕ_2 of the vertical emission fan. In other words, to collimate the horizontal emission fan, a lens with a smaller power (hence a longer focal length) than that of the lens 310 may be required.

5 [0044] Because of the asymmetric emission area and the asymmetric divergence angles of a laser source as described above, a return beam spot imaged onto a detector in a lidar system may also be asymmetric. For example, in the lidar system 100 illustrated in FIG. 1, with the spherical emission lens 130, the far-field beam spot at the object 150 may be asymmetric; consequently, the return beam spot imaged by the spherical receiving lens 140 onto the
10 detector 160a may also be asymmetric. Since the angular resolution of a lidar system may depend on the return beam spot size, an asymmetric return beam spot can limit the resolution of the lidar system.

I. OPTICAL DESIGNS FOR IMPROVED RESOLUTION

15 [0045] According to some embodiments of the present invention, a cylindrical lens with a negative power may be used in combination with a rotationally symmetric emission lens to achieve a relatively uniform angular resolution in the horizontal and vertical directions.

FIGS. 4A – 4B illustrate schematically an optical system for projecting a laser beam in a lidar system according to some embodiments. The optical system includes a plano-concave cylindrical lens 410 positioned in front of the laser source 210. The power axis of the cylindrical lens 410 may be substantially along the horizontal direction. That is, the cylindrical lens 410 may have a non-zero power in the horizontal direction as illustrated in
20 FIG. 4A, and has almost no power in the vertical direction as illustrated in FIG. 4B.

25 [0046] As illustrated in FIG. 4A, the cylindrical lens 410 may be configured to expand the angular divergence of the horizontal emission fan from ϕ_1 into ϕ_1' . The expanded horizontal emission fan may appear to be emitted from a virtual emission area that has a virtual width w' that is less than the actual width w . In some embodiments, the cylindrical lens 410 may be configured such that the virtual width w' is substantially equal to the height h of the vertical emission fan.

30 [0047] As illustrated in FIG. 4B, because the cylindrical lens 410 has no optical power in the vertical direction, the angular divergence ϕ_2 of the vertical emission fan is not affected by the cylindrical lens 410. In some embodiments, the expanded angular divergence ϕ_1' of the

horizontal emission fan may be substantially equal to the angular divergence ϕ_2 of the vertical emission fan. Thus, both the horizontal emission fan and the vertical emission fan may be collimated by the lens 310, as illustrated in FIGS. 4A – 4B.

[0048] Although FIGS. 4A – 4B shows an exemplary embodiment in which the cylindrical lens 410 has a plano-concave shape, other types of cylindrical lens (e.g., double-concave cylindrical lens or meniscus cylindrical lens) may be used according to some embodiments.

[0049] FIGS. 5A – 5D illustrate schematically the effect that the cylindrical lens 410 may have on the far-field beam spot shape. As illustrated in FIGS. 5A and 5C, without the cylindrical lens 410, the far-field beam spot 510 may be elongated in the horizontal direction because of the asymmetric emission area and the asymmetric divergence angles. As illustrated in FIG. 5B, by inserting the cylindrical lens 410 between the laser source 210 and the emission lens 310, light rays in the horizontal emission fan, as well as light rays in the vertical emission fan (not shown), may be collimated. As a result, the far-field beam spot 520 may be substantially symmetric in the horizontal and vertical directions, as illustrated in FIG. 5D.

[0050] Traditionally, a cylindrical lens with a positive power (e.g., a plano-convex cylindrical lens) is placed between a laser and a spherical collimating lens to circularize a laser beam. For example, a cylindrical lens with a positive power may be oriented such that the power axis is aligned with the vertical direction so as to reduce the divergence angle of the vertical emission fan. Consequently, a collimating lens with an increased focal length, as compared to the configuration illustrated in FIGS. 4A and 4B, may be required to collimate the laser beam. A longer focal length of the collimating lens may lead to a larger physical size of the lidar system, and thus may increase the manufacturing cost of the lidar system.

[0051] Using a cylindrical lens with a negative power may be particularly advantageous in a scanning lidar system. For example, in the scanning lidar system illustrated in FIG. 1, the emission lens 130 and the receiving lens 140 are fixed, while the laser sources 110a and 110b, and the detectors 160a and 160b are scanned in the focal planes of the emission lens 130 and the receiving lens 140, respectively. The scanning distance may be proportional to the focal length of the emission lens 130 for achieving a given angular field of view (FOV). Thus, by using an emission lens 130 with a shorter focal length, the scanning distance can be shortened while maintaining the same FOV.

[0052] FIG. 6A illustrates schematically an exemplary configuration of a laser source 610 and a cylindrical lens 640 that may be used in a lidar system. The laser source 610 may include a laser die 620 encapsulated by a transparent cover 630. According to some embodiments, the focal length of the cylindrical lens 640 may range from about -0.2 mm to 5 about -5 mm. For a cylindrical lens 640 with a plano-concave shape, as illustrated in FIG. 6A, the radius of curvature of the concave surface may range from about -0.1 mm to about -2 mm (e.g., about -0.5 mm). The cylindrical lens 640 may be placed at a distance d from the emission surface of the laser die 620 ranging from about 0.2 mm to about 5 mm (e.g., about 1 mm). It may be advantageous to place the cylindrical lens 640 in close proximity to the 10 emission surface of the laser die 620, so as to minimize certain undesirable optical effects of the cylindrical lens (e.g., slightly different best focus planes in the horizontal and vertical directions, which may be referred to as astigmatism). The distance d between the cylindrical lens 640 and the emission surface of the laser die 620 may be similar but not identical to the 15 focal length of the cylindrical lens 640, and may depend on the thickness of the cylindrical lens 640 and the shape of the cylindrical lens 640 (e.g., whether the cylindrical lens 640 is a plano-concave or double-concave).

[0053] FIG. 6B illustrates schematically another exemplary configuration of a laser source 650 and a cylindrical lens 670 according to some embodiments. Here, the cylindrical lens 670 is molded directly into the cover encapsulating the laser die 660. In some embodiments, 20 the focal length of the cylindrical lens 670 may range about -0.1 mm to about -2 mm. The distance d' between the apex of the concave surface and the emission surface of the laser die 660 may range from about 0.1 mm to about 2 mm. The distance d' may be similar but not identical to the focal length of the cylindrical lens 670.

[0054] FIG. 7A illustrates a cross-sectional view of an optical system for projecting a laser beam in a lidar system according to some embodiments. A cylindrical lens 720 is placed in 25 front of a laser source 710 (e.g., a laser diode). A spherical emission lens 730 is positioned in front of the cylindrical lens 720. The emission lens 730 may be a compound lens that includes several lens components. In some embodiments, the emission lens 730 may have a focal length ranging from about 5 mm to about 50 mm (e.g., about 16 mm). The diameter 30 (e.g., the aperture) of the emission lens 730 may range from about 5 mm to about 100 mm (e.g., 40 mm).

[0055] In some embodiments, a lidar system may include multiple laser sources arranged in an array that are projected by a single spherical emission lens. In such cases, each laser source may be paired with its own cylindrical lens. FIG. 7B illustrates an exemplary embodiment where a lidar system includes two laser sources 710a and 710b. A first cylindrical lens 720a is paired with the first laser source 710a, and a second cylindrical lens 720b is paired with the second laser source 710b. The two laser sources 710a and 710b share the same spherical emission lens 730.

[0056] FIG. 8 shows a simplified flowchart illustrating a method 800 of three-dimensional imaging using a lidar system according to some embodiments of the present invention.

10 **[0057]** The method 800 may include, at 802, translating a laser source and a cylindrical lens in unison. The laser source is translated to each of a plurality of emission locations in an emission plane. The laser source has an emission area with a first height and a first width greater than the first height. The cylindrical lens has a negative power and is positioned in front of the laser source. The cylindrical lens is oriented such that a power axis of the 15 cylindrical lens is substantially in a width direction. The cylindrical lens may be configured to transform the emission area of the laser source into a virtual emission area with a virtual width and a virtual height, where the virtual width is smaller than the first width of the emission area. The cylindrical lens may be a plano-concave cylindrical lens or a double-concave cylindrical lens. In some embodiments, the cylindrical lens may be integrated with 20 the laser source in a single package.

[0058] The method 800 may further include, at 804, emitting, using the laser source, a plurality of laser pulses. Each of the plurality of laser pulses is emitted at a respective one of the plurality of emission locations. The method 800 may further include, at 806, collimating and directing, using an emission lens, the plurality of laser pulses towards one or more 25 objects. The one or more objects may reflect each of the plurality of laser pulses to generate a plurality of return laser pulses.

[0059] The method 800 may further include, at 808, receiving and focusing, using a receiving lens, each of the plurality of return laser pulses to a plurality of corresponding detection locations in a detection plane. Each corresponding detection location is conjugate 30 with a respective emission location. In some embodiments, the receiving lens and the transmission lens may be the same lens; i.e., the same lens that is configured to collimate and

direct the plurality of laser pulses towards the one or more objects, as well as focusing the plurality of return laser pulses.

[0060] The method 800 may further include, at 810, translating a detector to each of the plurality of corresponding detection locations in the detection plane; and at 812, detecting, 5 using the detector, each respective return laser pulse of the plurality of return laser pulses at each respective detection location of the plurality of detection locations.

[0061] The method 800 may further include, at 814, determining, using a processor, a time of flight for each of the plurality of return laser pulses; and at 816, constructing, using the processor, a three-dimensional image of the one or more objects based on the time of flight 10 for each of the plurality of return laser pulses.

[0062] In some embodiments, each of the laser source and the detector are translated in one dimension or in two dimensions. In some embodiments, the laser source and the detector may be scanned in two directions in a Lissajous pattern. In some embodiments, the emission lens and the receiving lens are fixed while the laser source and the detector are being 15 translated.

[0063] In some other embodiments, the method 800 may further include translating the emission lens relative to the laser source in a plane substantially perpendicular to an optical axis of the emission lens; and translating the receiving lens relative to the detector in the plane synchronously with the translation of the emission lens. In some embodiments, each of 20 the emission lens and the receiving lens is translated in one dimension or two dimensions. In some embodiments, the emission lens and the receiving lens may be scanned in two directions in a Lissajous pattern.

[0064] It should be appreciated that the specific steps illustrated in FIG. 8 provide a particular method of performing three-dimensional imaging using a lidar system according to 25 some embodiments of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 8 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added 30 and some steps may be removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

II. DETECTOR DESIGNS FOR IMPROVED RESOLUTION

[0065] According to some embodiments, another approach to improve the resolution of a lidar system may be implemented on the detector side. As illustrated in FIGS. 5A and 5C, without using a cylindrical lens, the far-field beam spot 510 may be elongated in the horizontal direction. As a result, an image of the far-field beam spot 510 formed by a receiving lens (e.g., the receiving lens 140 illustrated in FIG. 1) on a detector (e.g., the detector 160a or 160b illustrated in FIG. 1) may also be elongated in the horizontal direction.

[0066] FIG. 9 illustrates schematically a lidar system 900 according to some embodiments. Similar to the lidar system 100 illustrated in FIG. 1, the lidar system 900 may include a laser source 910, and an emission lens 930 for collimating a laser beam emitted by the laser source 910. The collimated laser beam may be reflected off of one or more objects 950a and 950b. The lidar system 900 may further include a receiving lens 940 for focusing the return laser beam, and a detector 920 positioned at a focal plane of the receiving lens 940 for detecting the focused return laser beam. As discussed above, because of the asymmetric profile of the emitted laser beam, the focused spot of the return laser beam at the detector 920 may be elongated. FIG. 10 illustrates schematically a return beam spot 1010 imaged at the focal plane of the receiving lens 940 that is elongated in the horizontal direction.

[0067] According to some embodiments, the detector 920 may include an array of photo sensors. For example, the detector 920 may include two photo sensors 922a and 922b arranged next to each other as a one-dimensional array in the horizontal direction. As illustrated in FIGS. 9 and 10, each photo sensor 922a or 922b has a sensing area that covers a portion of the return beam spot 1010. Thus, the first photo sensor 922a may detect the left half of the return laser beam, and the second photo sensor 922b may detect the right half of the return laser beam.

[0068] As an illustrative example, FIG. 9 shows that the laser beam may be projected onto two objects 950a and 950b (e.g., two people) located within the FOV 960 of the laser beam in the far-field. The laser spot size in the far-field may be approximately equal to the dimension of the emission area of the laser source times the distance from the laser source to the object, and divided by the focal length of the emission lens 930. A first portion of the return laser beam that is reflected off of the first object 950a (represented by the light rays illustrated with the solid lines) may be imaged onto the left half of the return beam spot 1010; and a second portion of the return laser beam that is reflected off of the second object 950b (represented by

the light rays illustrated with the dashed lines) may be imaged onto the right half of the return beam spot 1010. As illustrated in FIGS. 9 and 10A, the first photo sensor 922a may detect the first portion of the return laser beam reflected off of the first object 950a, and the second photo sensor 922b may detect the second portion of the return laser beam reflected off of the 5 second object 950b. Therefore, the lidar system 900 may be able to resolve the two objects 950a and 950b. It should be understood that “vertical” and “horizontal” orientations may be switched in the context of the drawings and description, or the orientation may be arbitrarily rotated, as would be apparent to one skilled in the art.

[0069] For comparison, FIG. 10B illustrates a detector 1020 that includes a single photo 10 sensor 1030 with a sensing area that encompass the entire return beam spot 1010. In this configuration, the lidar system 900 may not be able to resolve the two objects 950a and 950b, as a single return laser pulse may be detected by the detector 1020. Thus, by having two photo sensors 922a and 922b arranged as an array in the horizontal direction as illustrated in FIGS. 9 and 10A, the resolution of the lidar system 900 in the horizontal direction may be 15 approximately doubled as compared to a detector 1020 with a single photo sensor 1030.

[0070] According to some embodiments, the detector 920 may have separate outputs for the individual photo sensors, so that the time of flight for each portion of the return laser pulse detected by each photo sensor may be determined independently. FIGS. 11A – 11C illustrate schematically timing diagrams of laser pulses for the example illustrated in FIGS. 9 and 10. As illustrated in FIG. 11A, a laser pulse 1110 may be emitted by the laser source 910 at a first instance of time t_1 . The laser pulse 1110 may be reflected off of the first object 950a and the second object 950b. As illustrated in FIG. 11B, a first portion of the return laser pulse reflected off of the first object 950a may be detected by the first photo sensor 922a at a second instance of time t_2 . The time elapsed between t_1 and t_2 may be determined as Δt_1 . A 20 distance L_1 between the lidar system 900 and the first object 950a may be determined based on Δt_1 . Similarly, as illustrated in FIG. 11C, a second portion of the return laser pulse reflected off of the second object 950b may be detected by the second photo sensor 922b at a third instance of time t_3 . The time elapsed between t_1 and t_3 may be determined as Δt_2 . A 25 distance L_2 between the lidar system 900 and the second object 950b may be determined based on Δt_2 . Therefore, by having two photo sensors 922a and 922b in the detector 920 with separate outputs, the lidar system 900 may be able to resolve the different distances L_1 and L_2 30 of the two objects 950a and 950b.

[0071] FIG.12A shows a schematic plan view of a detector 1210 according to some embodiments. The detector 1210 may include a one-dimensional array of photo sensors, such as a 1×2 array that includes the photo sensors 1212a and 1212b. Although a 1×2 array of photo sensors is illustrated in FIG.12A, the detector 1210 may include a 1×3 array of photo sensors, a 1×4 array of photo sensors, or the like. For example, by using a 1×3 array, an approximately three-fold improvement of the resolution in the direction of the array may be achieved.

[0072] FIG.12B shows a schematic plan view of a detector 1220 according to some embodiments. The detector 1220 may include a two-dimensional array, such as a 2×3 array that includes photo sensors 1222a – 1222f. Thus, an approximately two-fold improvement of the resolution in one direction, and an approximately three-fold improvement of the resolution in the orthogonal direction may be achieved. Although a 2×3 array of photo sensors is illustrated in FIG.12B, the detector 1220 may include a 2×4 array of photo sensors, a 2×5 array of photo sensors, or other configurations, according to various embodiments.

[0073] In some embodiments, the array of photo sensors may be configured such that the total surface area of the array approximately matches that of the image spot of the return laser beam formed by the receiving lens 940. For example, if the image spot has a 1×2 aspect ratio, the detector may include a 1×2 array of photo sensors or a 2×4 array of photo sensors (assuming that the surface area of each photo sensor is a square). Dead space between photo sensors may be advantageously reduced or minimized to avoid loss of detection efficiency.

[0074] According to various embodiments, the photo sensors may include photodiodes, phototransistors, photoresistors, photomultiplier tubes, microchannel plate detectors, charge-coupled devices (CCDs), and the like.

[0075] According to some other embodiments, a bi-cell or a quad-cell detector may be used. In such cases, the detector includes a single detector designed to have multiple outputs corresponding to the locations where light is incident on the detector.

[0076] The array detector concept described above may be extended to lidar systems that include multiple laser sources and multiple detectors. In such cases, each laser source may be paired with its own array detector. For example, referring to FIG. 1, a first laser source 110a may be paired with a first detector 160a, and a second laser source 110b may be paired with a second detector 160b, where each of the first detector 160a and the second detector 160b includes a photo sensor array.

[0077] According to some embodiments, an array detector may be used in a lidar system in combination with a collimating optical system that includes a cylindrical lens (e.g., as discussed above with references to FIGS. 4A – 4B, 6A – 6B, and 7) for further resolution improvement.

5 **[0078]** FIG. 13 illustrates schematically a lidar system 1300 according to some embodiments of the present invention. The lidar system 1300 include a laser source 1310 and a detector 1320. Instead of having separate emission lens and receiving lens as illustrated in FIGS. 1 and 9, the lidar system 1300 includes a single lens 1330 for collimating a laser beam emitted by the laser source 1310, as well as for focusing a return laser beam reflected off of 10 one or more objects. The lidar system 1300 may include a beam splitter 1350 positioned between the laser source 1310 and the lens 1330. The beam splitter 1350 may be configured to partially transmit the laser beam emitted by the laser source 1310, and partially reflect the return laser beam toward the detector 1320.

15 **[0079]** In some embodiments, the lidar system 1300 may further include an optional cylindrical lens 1340 positioned in front of the laser source 1310. The cylindrical lens 1340 has a negative power, similar to the cylindrical lens 410 illustrated in FIGS. 4A and 4B. As described above in relation to FIGS. 4A and 4B, the cylindrical lens 1340 may result in a relatively symmetric far-field beam spot, as illustrated in FIG. 5D.

20 **[0080]** In some embodiments, the detector 1320 may include a plurality of photo sensors 1322 and 1324 arranged as an array, similar to the detector 920 illustrated in FIGS. 9, 10A, and 12A – 12B. As described above in relation to FIG. 9, each photo sensor 1322 or 1324 may be configured to detect a respect portion of the return laser beam. By having both the cylindrical lens 1340 and the array detector 1320, the lidar system 1300 may achieve even better resolution than a lidar system that only includes a cylindrical lens or a lidar system that 25 only includes an array detector.

[0081] FIG. 14 shows a simplified flowchart illustrating a method 1400 of three-dimensional imaging using a lidar system according to some embodiments of the present invention.

30 **[0082]** The method 1400 may include, at 1402, emitting, using a laser source, a laser pulse; and at 1404, collimating and directing, using an emission lens, the laser pulse towards one or more objects within a field of view of the laser pulse. The one or more objects may reflect the laser pulse to generate a return laser pulse.

[0083] The method 1400 may further include, at 1406, receiving and focusing, using a receiving lens, the return laser pulse to a return beam spot at a focal plane of the receiving lens; and at 1408, detecting, using a detector that includes a plurality of photo sensors arranged as an array at the focal plane of the receiving lens, a respective portion of the return 5 laser pulse received at each respective photo sensor. The respective portion of the return laser pulse corresponds to a respective section of the field of view of the laser pulse.

[0084] The method 1400 may further include, at 1410, determining, using a processor coupled to the laser source and the detector, a time of flight for each respective portion of the return laser pulse; and at 1412, constructing, using the processor, a three-dimensional image 10 of the one or more objects based on the time of flight for each respective portion of the return laser pulse.

[0085] In some embodiments, each respective photo sensor of the detector has a respective sensing area for receiving the respective portion of the return laser pulse. The plurality of photo sensors is arranged such that a total sensing area of the plurality of photo sensors 15 substantially matches the return beam spot.

[0086] In some embodiments, the method 1400 may further include translating the laser source through a plurality of emission locations in an emission plane substantially perpendicular to an optical axis of the emission lens, and translating the detector through a plurality of detection locations in the focal plane of the receiving lens. Each respective 20 detection location of the plurality of detection locations corresponds to a respective emission location of the plurality of emission locations. In some embodiments, each of the laser source and the detector is translated in one dimension or in two dimensions. In some embodiments, the laser source and the detector may be scanned in two directions in a Lissajous pattern. In some embodiments, the emission lens and the receiving lens are fixed 25 while the laser source and the detector are being translated.

[0087] In some other embodiments, the method 1400 may further include translating the emission lens relative to the laser source in a plane substantially perpendicular to an optical axis of the emission lens; and translating the receiving lens relative to the detector in the plane synchronously with the translation of the emission lens. In some embodiments, each of 30 the emission lens and the receiving lens is translated in one dimension or two dimensions. In some embodiments, the emission lens and the receiving lens may be scanned in two directions in a Lissajous pattern. In some embodiments, the laser source and the detector are

also translated synchronously with respect to each other, while the emission lens and the receiving lens are being translated.

[0088] In some further embodiments, the method 1400 may further include translating the laser source and the detector synchronously in a first direction substantially perpendicular to an optical axis of the emission lens; and translating the emission lens and the receiving lens synchronously in a second direction orthogonal to the first direction and substantially perpendicular to the optical axis of the emission lens. One of ordinary skill in the art would recognize many variations, alternatives, and modifications.

[0089] It should be appreciated that the specific steps illustrated in FIG. 14 provide a particular method of performing three-dimensional imaging using a lidar system according to some embodiments of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 14 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added and some steps may be removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0090] The specific details of particular embodiments may be combined in any suitable manner without departing from the spirit and scope of embodiments of the invention. However, other embodiments of the invention may be directed to specific embodiments relating to each individual aspect, or specific combinations of these individual aspects.

[0091] A recitation of “a”, “an” or “the” is intended to mean “one or more” unless specifically indicated to the contrary.

[0092] Ranges may be expressed herein as from “about” one specified value, and/or to “about” another specified value. The term “about” is used herein to mean approximately, in the region of, roughly, or around. When the term “about” is used in conjunction with a numerical range, it modifies that range by extending the boundaries above and below the numerical values set forth. In general, the term “about” is used herein to modify a numerical value above and below the stated value by a variance of 10%. When such a range is expressed, another embodiment includes from the one specific value and/or to the other specified value. Similarly, when values are expressed as approximations, by use of the antecedent “about,” it will be understood that the specified value forms another embodiment.

It will be further understood that the endpoints of each of the ranges are included with the range.

[0093] The above description of exemplary embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form described, and many modifications and variations are possible in light of the teaching above. The embodiments were chosen and described in order to explain the principles of the invention and its practical applications to thereby enable others skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated.

WHAT IS CLAIMED IS:

- 1 1. An optical system comprising:
 - 2 a laser source having an emission area that has a first width in a first direction
 - 3 and a first height in a second direction orthogonal to the first direction, the first width being
 - 4 greater than the first height;
 - 5 a cylindrical lens having a negative power and positioned in front of the laser
 - 6 source, the cylindrical lens being oriented such that a power axis of the cylindrical lens is
 - 7 substantially along the first direction, the cylindrical lens configured to transform the
 - 8 emission area of a laser beam emitted by the laser source into a virtual emission area having a
 - 9 virtual width and a virtual height, the virtual width being less than the first width; and
 - 10 an rotationally symmetric lens positioned downstream from the cylindrical
 - 11 lens, the rotationally symmetric lens configured to collimate and direct the laser beam
 - 12 towards a far-field.
- 1 2. The optical system of claim 1 wherein the laser source comprises a
- 2 solid state laser source.
- 1 3. The optical system of claim 2 wherein the cylindrical lens is integrated
- 2 with the laser source in a single package.
- 1 4. The optical system of claim 1 wherein the laser source, the cylindrical
- 2 lens, and the rotationally symmetric lens are used in a lidar system.
- 1 5. The optical system of claim 4 wherein the laser source and the
- 2 cylindrical lens are configured to be translated in unison in a focal plane of the rotationally
- 3 symmetric lens so as to scan the laser beam.
- 1 6. The optical system of claim 4 further comprising:
 - 2 a second laser source arranged next to the laser source, such that the laser
 - 3 source and the second laser source form a laser array; and
 - 4 a second cylindrical lens positioned in front of the second laser source and
 - 5 configured to transform a second emission area of a second laser beam emitted by the second
 - 6 laser source into a second virtual emission area;
 - 7 wherein rotationally symmetric lens is further configured to collimate and
 - 8 direct the second laser beam towards the far-field.

1 7. A lidar system for three-dimensional imaging, the lidar system
2 comprising:

3 a laser source configured to emit a plurality of laser pulses, the laser source
4 having an emission area that has a first width in a first direction and a first height in a second
5 direction orthogonal to the first direction, the first width being greater than the first height;

6 a cylindrical lens having a negative power and positioned in front of the laser
7 source, the cylindrical lens being oriented such that a power axis of the cylindrical lens is
8 substantially along the first direction, the cylindrical lens configured to transform the
9 emission area into a virtual emission area having a virtual width and a virtual height, the
10 virtual width being less than the first width;

11 an emission lens positioned downstream from the cylindrical lens, the
12 emission lens being rotationally symmetric and configured to collimate and direct the
13 plurality of laser pulses towards one or more objects, the one or more objects reflecting the
14 plurality of laser pulses to generate a plurality of return laser pulses;

15 a receiving lens being rotationally symmetric and configured to receive and
16 focus each of the plurality of return laser pulses to a return beam spot at a focal plane of the
17 receiving lens;

18 a detector having a detection surface positioned at the focal plane of the
19 receiving lens and configured to receive and detect each of the plurality of return laser pulses;
20 and

21 a processor coupled to the laser source and the detector, the processor
22 configured to:

23 determine a time of flight for each of the plurality of return laser
24 pulses; and

25 construct a three-dimensional image of the one or more objects based
26 on the determined time of flight for each of the plurality of return laser pulses.

1 8. The lidar system of claim 7 wherein the cylindrical lens is integrated
2 with the laser source in a single package.

1 9. The lidar system of claim 7 wherein:

2 the laser source, together with the cylindrical lens, is configured to be
3 translated in at least one direction substantially perpendicular to an optical axis of the lidar

4 system through a plurality of emission locations, each of the plurality of laser pulses being
5 emitted at a respective one of the plurality of emission locations; and

6 the detector is configured to be translated in the at least one direction through
7 a plurality of detection locations in the focal plane of the receiving lens, each respective
8 detection location of the plurality of detection locations corresponding to a respective
9 emission location of the plurality of emission locations, wherein the laser source and the
10 detector are translated synchronously with respect to each other.

1 10. The lidar system of claim 9 wherein each of the laser source and the
2 detector is configured to be translated in two directions.

1 11. The lidar system of claim 10 wherein each of the laser source and the
2 detector is configured to be translated in a Lissajous pattern.

1 12. The lidar system of claim 7 wherein the emission lens is configured to
2 be translated relative to the laser source in at least one direction substantially perpendicular to
3 an optical axis of the emission lens, and the receiving lens is configured to be translated
4 relative to the detector in the at least one direction, wherein the emission lens and the
5 receiving lens are translated synchronously with respect to each other.

1 13. The lidar system of claim 12 wherein each of the emission lens and the
2 receiving lens is translated in two directions.

1 14. The lidar system of claim 13 wherein each of the emission lens and the
2 receiving lens is translated in a Lissajous pattern.

1 15. The lidar system of claim 7 wherein the laser source and the detector
2 are configured to be translated synchronously in at least a first direction substantially
3 perpendicular to an optical axis of the lidar system, and the emission lens and the receiving
4 lens are configured to be translated synchronously in at least a second direction substantially
5 perpendicular to the optical axis of the lidar system.

1 16. A method of three-dimensional imaging, the method comprising:
2 translating a laser source and a cylindrical lens in unison, the laser source
3 having an emission area with a first height and a first width greater than the first height, the
4 cylindrical lens having a negative power and positioned in front of the laser source, the

5 cylindrical lens being oriented such that a power axis of the cylindrical lens is substantially in
6 a width direction, wherein the laser source is translated to each of a plurality of emission
7 locations in an emission plane;

8 emitting, using the laser source, a plurality of laser pulses, each of the plurality
9 of laser pulses being emitted at a respective one of the plurality of emission locations;

10 collimating and directing, using an emission lens, the plurality of laser pulses
11 towards one or more objects, the one or more objects reflecting each of the plurality of laser
12 pulses to generate a plurality of return laser pulses;

13 receiving and focusing, using a receiving lens, each of the plurality of return
14 laser pulses to a plurality of corresponding detection locations in a detection plane, each
15 corresponding detection location being conjugate with a respective emission location;

16 translating a detector to each of the plurality of corresponding detection
17 locations in the detection plane;

18 detecting, using the detector, each respective return laser pulse of the plurality
19 of return laser pulses at each respective detection location of the plurality of detection
20 locations;

21 determining, using a processor, a time of flight for each of the plurality of
22 return laser pulses; and

23 constructing, using the processor, a three-dimensional image of the one or
24 more objects based on the time of flight for each of the plurality of return laser pulses.

1 17. The method of claim 16 wherein the receiving lens and the emission
2 lens comprise a same lens.

1 18. The method of claim 16 wherein the cylindrical lens is configured to
2 transform the emission area of the laser source into a virtual emission area having a virtual
3 width and a virtual height, the virtual width being smaller than the first width of the emission
4 area.

1 19. The method of claim 16 wherein the laser source and the detector are
2 translated in at least a first direction substantially perpendicular to an optical axis of the
3 emission lens.

1 20. The method of claim 19 further comprising translating the emission
2 lens and the receiving lens synchronously in at least a second direction substantially
3 perpendicular to the optical axis of the emission lens.

1 21. The method of claim 16 wherein each of the laser source and the
2 detector is translated two dimensions.

1 22. The method of claim 21 wherein each of the laser source and the
2 detector is configured to be translated in a Lissajous pattern.

1 23. The method of claim 16 wherein the cylindrical lens is integrated with
2 the laser source in a single package.

1 24. A lidar system for three-dimensional imaging, the lidar system
2 comprising:

3 a laser source configured to emit a laser beam carrying an electromagnetic
4 signal;

5 an emission lens configured to collimate and direct the laser beam towards one
6 or more objects within a field of view of the laser beam, the one or more objects reflecting
7 the laser beam to generate a return laser beam;

8 a receiving lens configured to receive and focus the return laser beam to a
9 return beam spot at a focal plane of the receiving lens;

10 a detector including a plurality of photo sensors arranged as an array at the
11 focal plane of the receiving lens, each respective photo sensor having a respective sensing
12 area and configured to receive and detect a respective portion of the return laser beam
13 corresponding to a respective section of the field of view of the laser beam; and

14 a processor coupled to the laser source and the detector, the processor
15 configured to:

16 determine a respective time of flight for each respective portion of the
17 return laser beam detected at the respective photo sensor of the detector; and

18 construct a three-dimensional image of the one or more objects based
19 on the respective time of flight for each respective portion of the return laser beam.

1 25. The lidar system of claim 24 wherein the plurality of photo sensors are
2 arranged such that a total sensing area of the plurality of photo sensors substantially matches
3 the return beam spot.

1 26. The lidar system of claim 24 wherein the plurality of photo sensors is
2 arranged as the array that is one-dimensional or two-dimensional.

1 27. The lidar system of claim 26 wherein the plurality of photo sensors
2 comprises two photo sensors.

1 28. The lidar system of claim 24 wherein the emission lens and the
2 receiving lens comprise a same lens.

1 29. The lidar system of claim 24 further comprising a scanning mechanism
2 to scan the laser beam emitted by the laser source to cover a second field of view.

1 30. The lidar system of claim 29 wherein the scanning mechanism
2 comprises a rotating frame, wherein the laser source, the emission lens, the receiving lens,
3 and the detector are mounted on the rotating frame.

1 31. The lidar system of claim 29 wherein the scanning mechanism
2 comprises a rotating mirror or a micro-electro-mechanical systems (MEMS) mirror
3 configured to reflect the laser beam.

1 32. The lidar system of claim 29 wherein the scanning mechanism is
2 configured to translate the emission lens and the receiving lens synchronously in a plane
3 substantially perpendicular to an optical axis of the lidar system.

1 33. The lidar system of claim 29 wherein the scanning mechanism is
2 configured to:
3 translate the laser source relative to the emission lens in a plane substantially
4 perpendicular to an optical axis of the lidar system; and

5 translate the detector relative to the receiving lens in the plane in
6 synchronization of the translation of the laser source.

1 34. The lidar system of claim 29 wherein the scanning mechanism is
2 configured to:

3 translate the laser source and the detector synchronously in at least a first
4 direction in a plane substantially perpendicular to an optical axis of the lidar system; and
5 translate the emission lens and the receiving lens synchronously in at least a
6 second direction in the plane.

- 1 36. A method of three-dimensional imaging, the method comprising:
- 2 emitting, using a laser source, a laser pulse;
- 3 collimating and directing, using an emission lens, the laser pulse towards one
- 4 or more objects within a field of view of the laser pulse, the one or more objects reflecting the
- 5 laser pulse to generate a return laser pulse;
- 6 receiving and focusing, using a receiving lens, the return laser pulse to a return
- 7 beam spot at a focal plane of the receiving lens;
- 8 detecting, using a detector including a plurality of photo sensors arranged as
- 9 an array at the focal plane of the receiving lens, a respective portion of the return laser pulse
- 10 received at each respective photo sensor, wherein the respective portion of the return laser
- 11 pulse corresponds to a respective section of the field of view of the laser pulse;
- 12 determining, using a processor coupled to the laser source and the detector, a
- 13 time of flight for each respective portion of the return laser pulse; and
- 14 constructing, using the processor, a three-dimensional image of the one or
- 15 more objects based on the time of flight for each respective portion of the return laser pulse.

1 37. The method of claim 36 wherein each respective photo sensor has a
2 respective sensing area for receiving the respective portion of the return laser pulse, and the
3 plurality of photo sensors is arranged such that a total sensing area of the plurality of photo
4 sensors substantially matches the return beam spot.

1 38. The method of claim 37 wherein the return beam spot has a width in a
2 first detector direction and a height in a second detector direction orthogonal to the first
3 detector direction, the height being different from the width.

1 40. The method of claim 36 further comprising:

2 translating the laser source through a plurality of emission locations along at

3 least a first direction substantially perpendicular to an optical axis of the emission lens; and

4 translating the detector through a plurality of detection locations along at least

5 the first direction, each respective detection location of the plurality of detection locations

6 corresponding to a respective emission location of the plurality of emission locations,

7 wherein the laser source and the detector are translated synchronously with respect to each

8 other.

1 41. The method of claim 36 wherein each of the laser source and the

2 detector is translated along two directions.

1 42. The method of claim 36 further comprising:

2 translating the emission lens relative to the laser source along at least a first

3 direction substantially perpendicular to an optical axis of the emission lens; and

4 translating the receiving lens relative to the detector along at least the first

5 direction, wherein the emission lens and the receiving lens are translated synchronously with

6 respect to each other.

1 43. The method of claim 42 wherein each of the emission lens and the

2 receiving lens is translated along two directions.

1 44. The method of claim 36 further comprising:

2 translating the laser source and the detector synchronously in at least a first

3 direction substantially perpendicular to an optical axis of the emission lens; and

4 translating the emission lens and the receiving lens synchronously in at least a

5 second direction substantially perpendicular to the optical axis of the emission lens.

1 45. A lidar system for three-dimensional imaging, the lidar system

2 comprising:

3 a laser source configured to emit a laser beam carrying an electromagnetic

4 signal;

5 a lens configured to collimate and direct the laser beam towards one or more

6 objects within a field of view of the laser beam, the one or more objects reflecting the laser

7 beam to generate a return laser beam, the lens further configured to receive and focus the
8 return laser beam to a return beam spot at a focal plane of the lens;

9 a detector including a plurality of photo sensors arranged as an array at the
10 focal plane of the lens, each respective photo sensor having a respective sensing area and
11 configured to receive and detect a respective portion of the return laser beam corresponding
12 to a respective section of the field of view of the laser beam; and

13 a processor coupled to the laser source and the detector, the processor
14 configured to:

15 determine a respective time of flight for each respective portion of the
16 return laser beam detected at the respective photo sensor of the detector; and

17 construct a three-dimensional image of the one or more objects based
18 on the respective time of flight for each respective portion of the return laser beam.

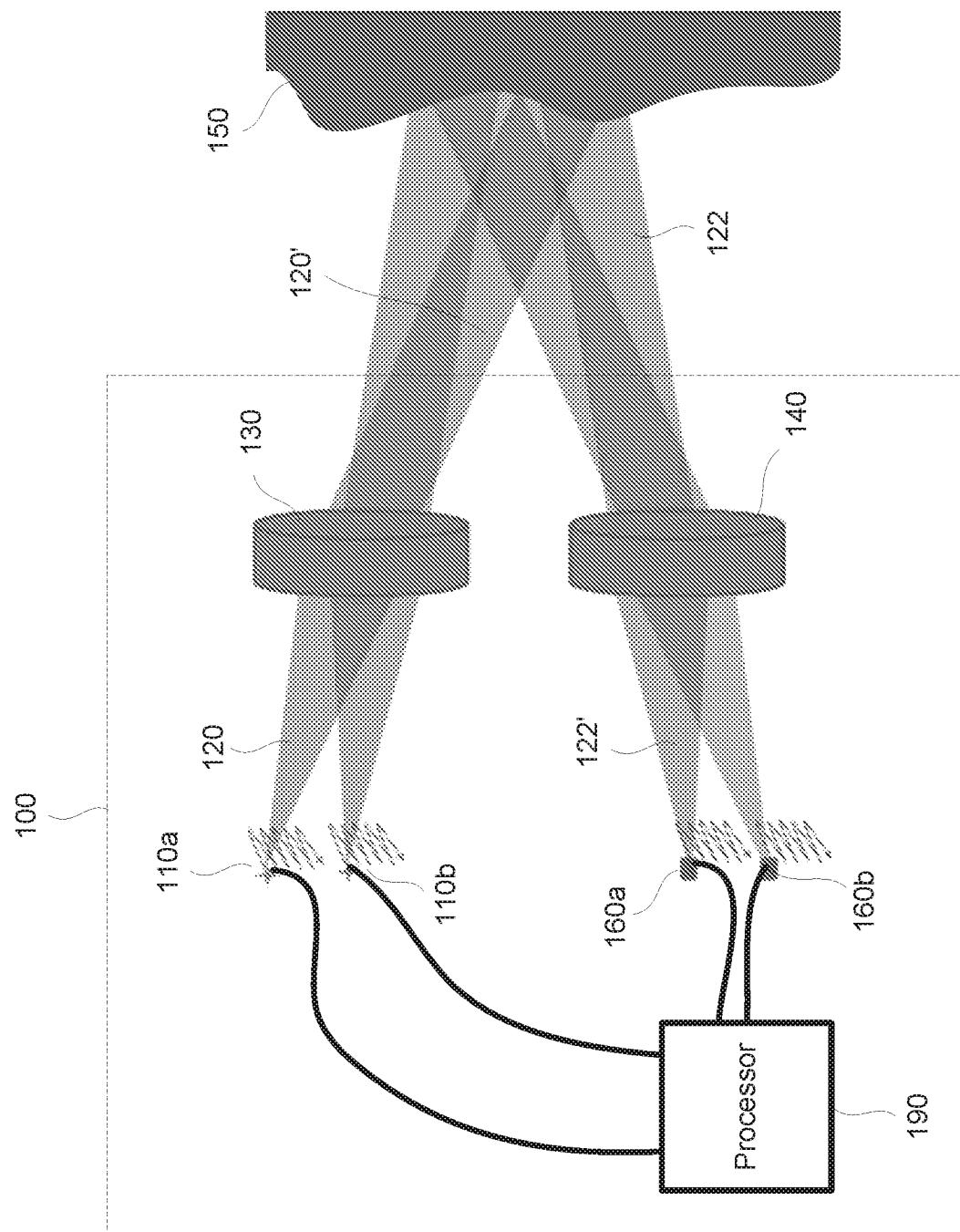


FIG. 1

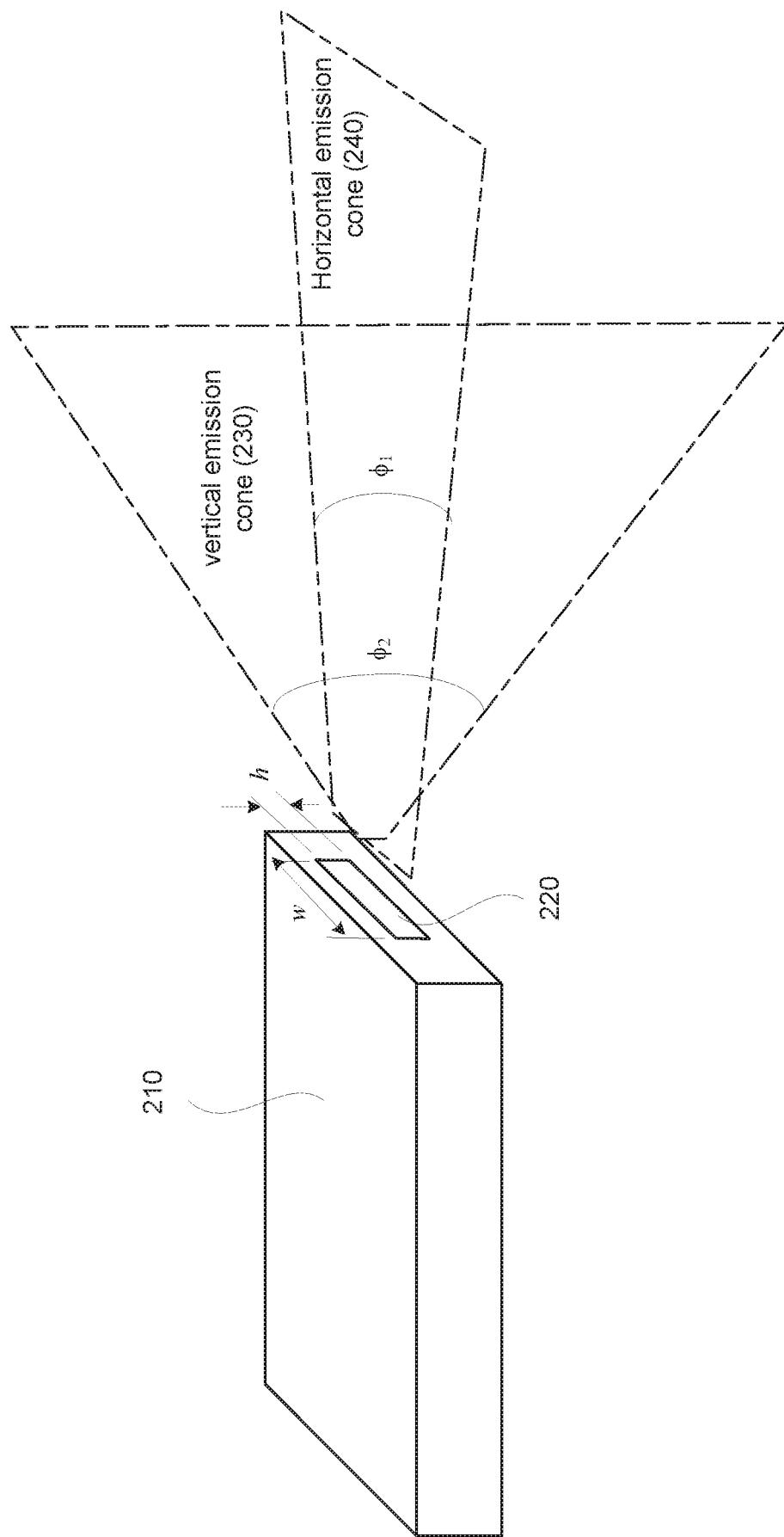


FIG. 2

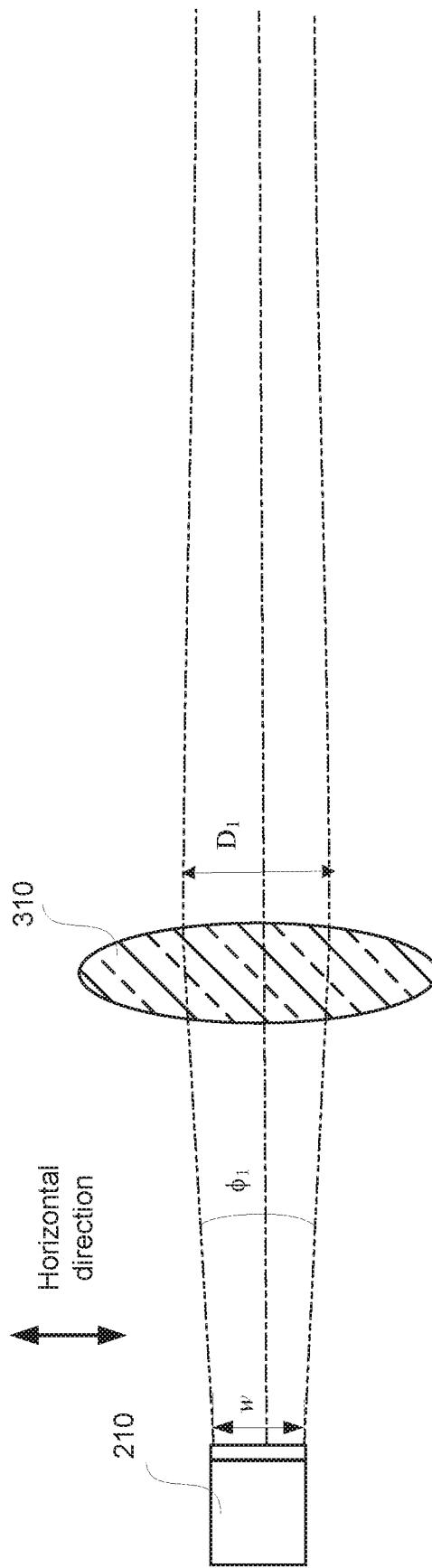


FIG. 3A

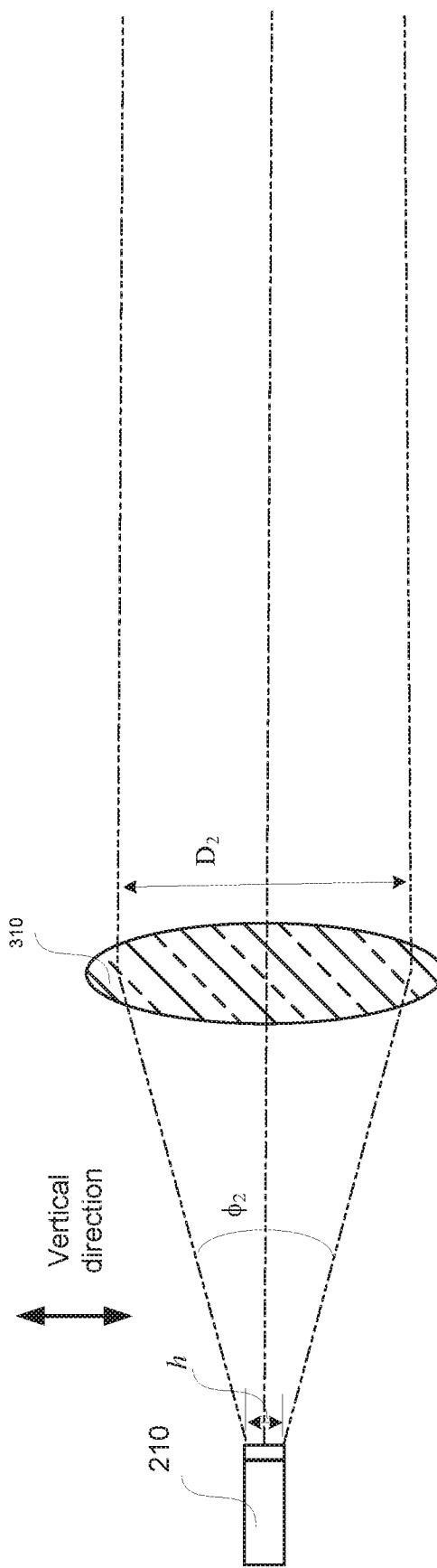


FIG. 3B

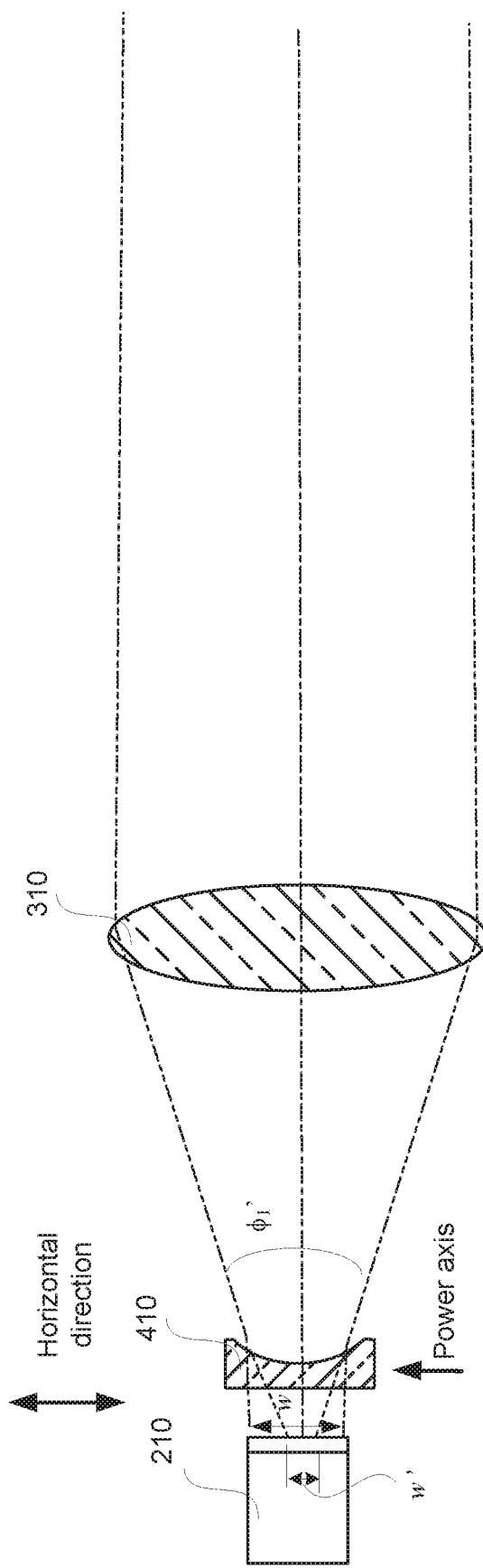


FIG. 4A

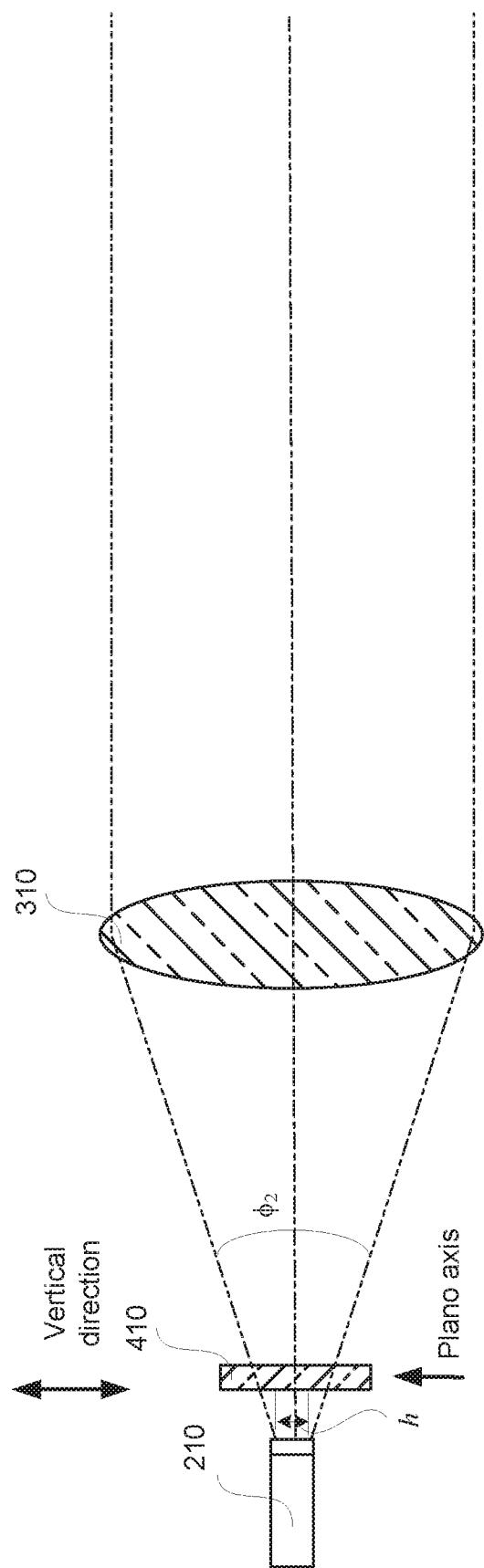


FIG. 4B

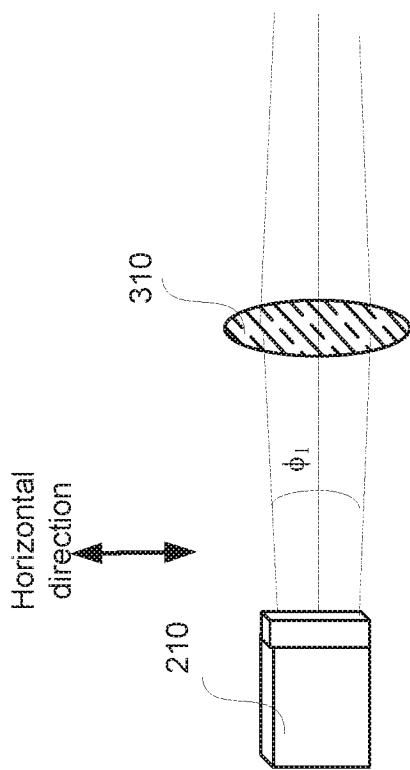


FIG. 5A

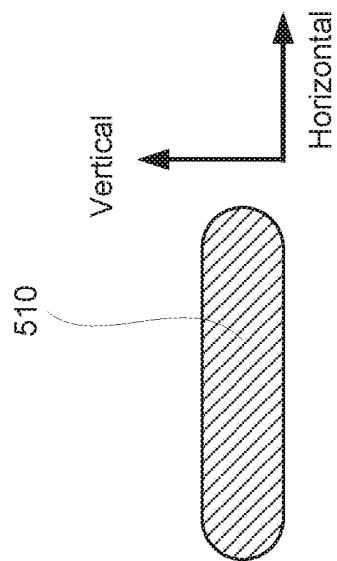


FIG. 5C

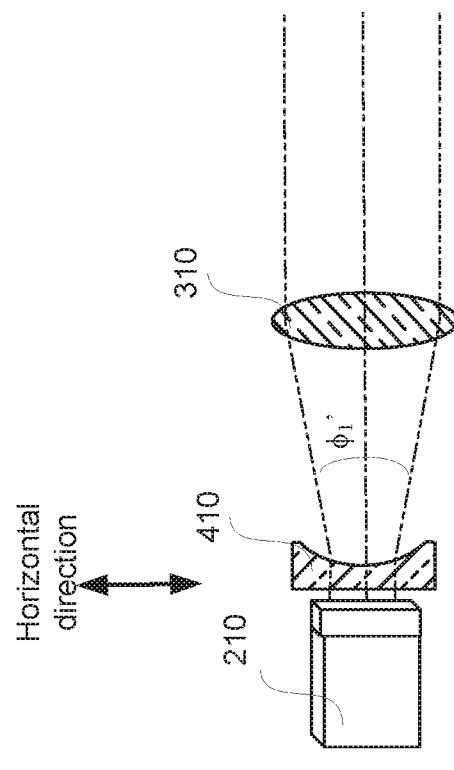


FIG. 5B

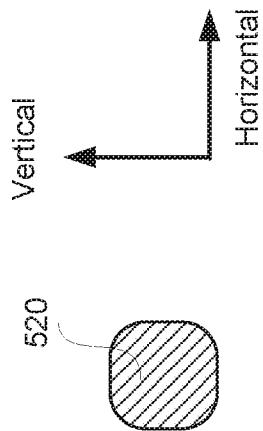


FIG. 5D

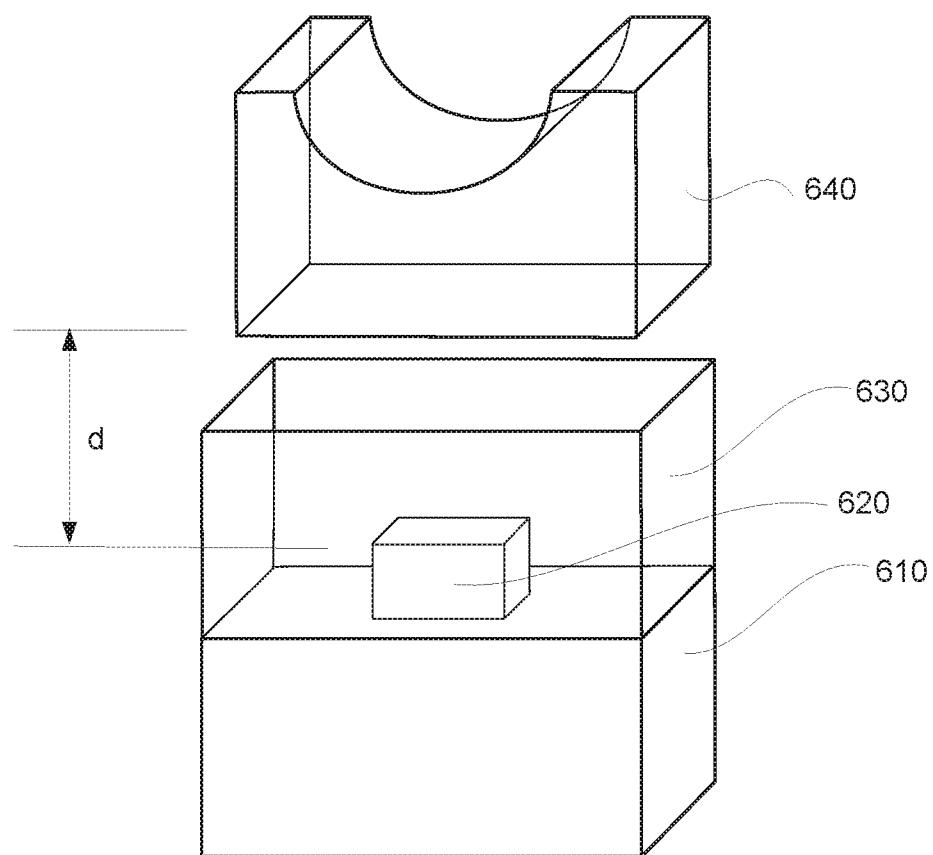


FIG. 6A

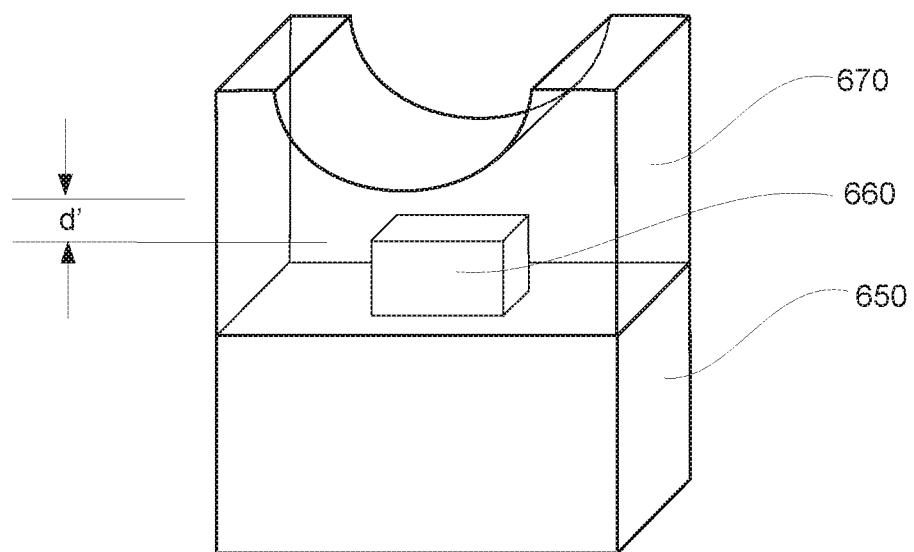


FIG. 6B

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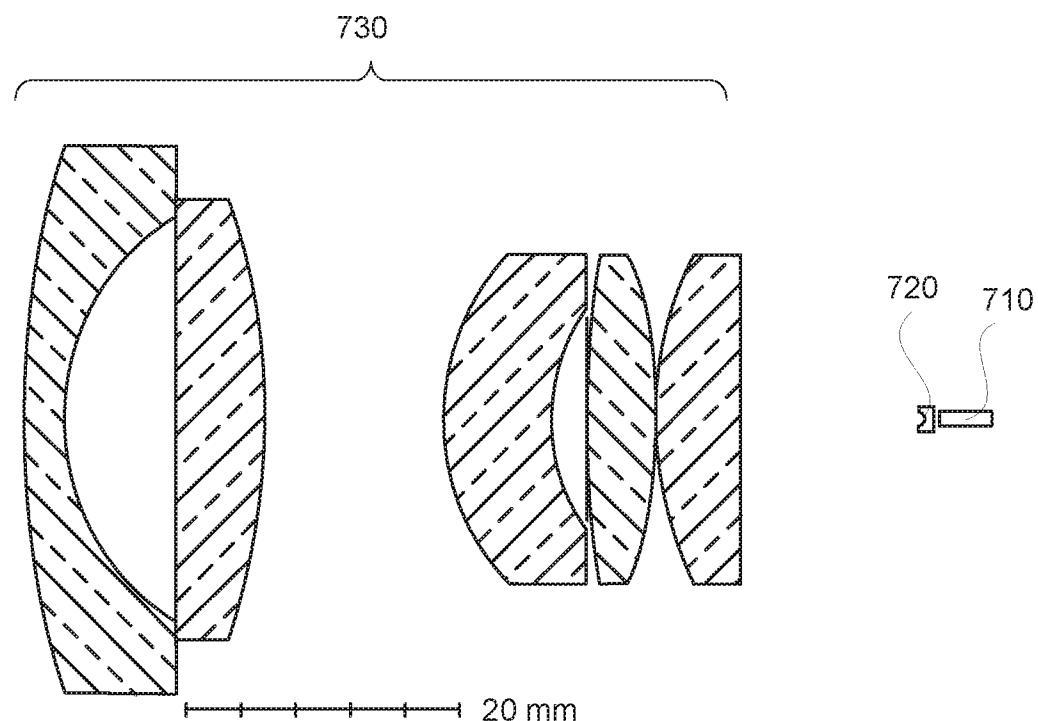


FIG. 7A

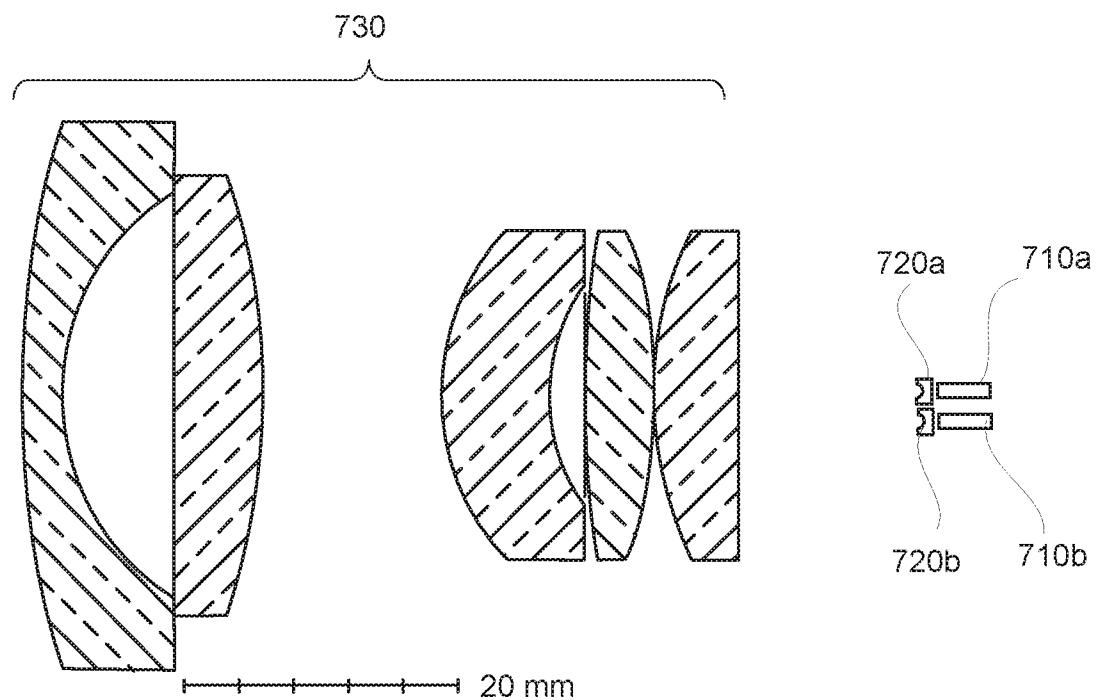
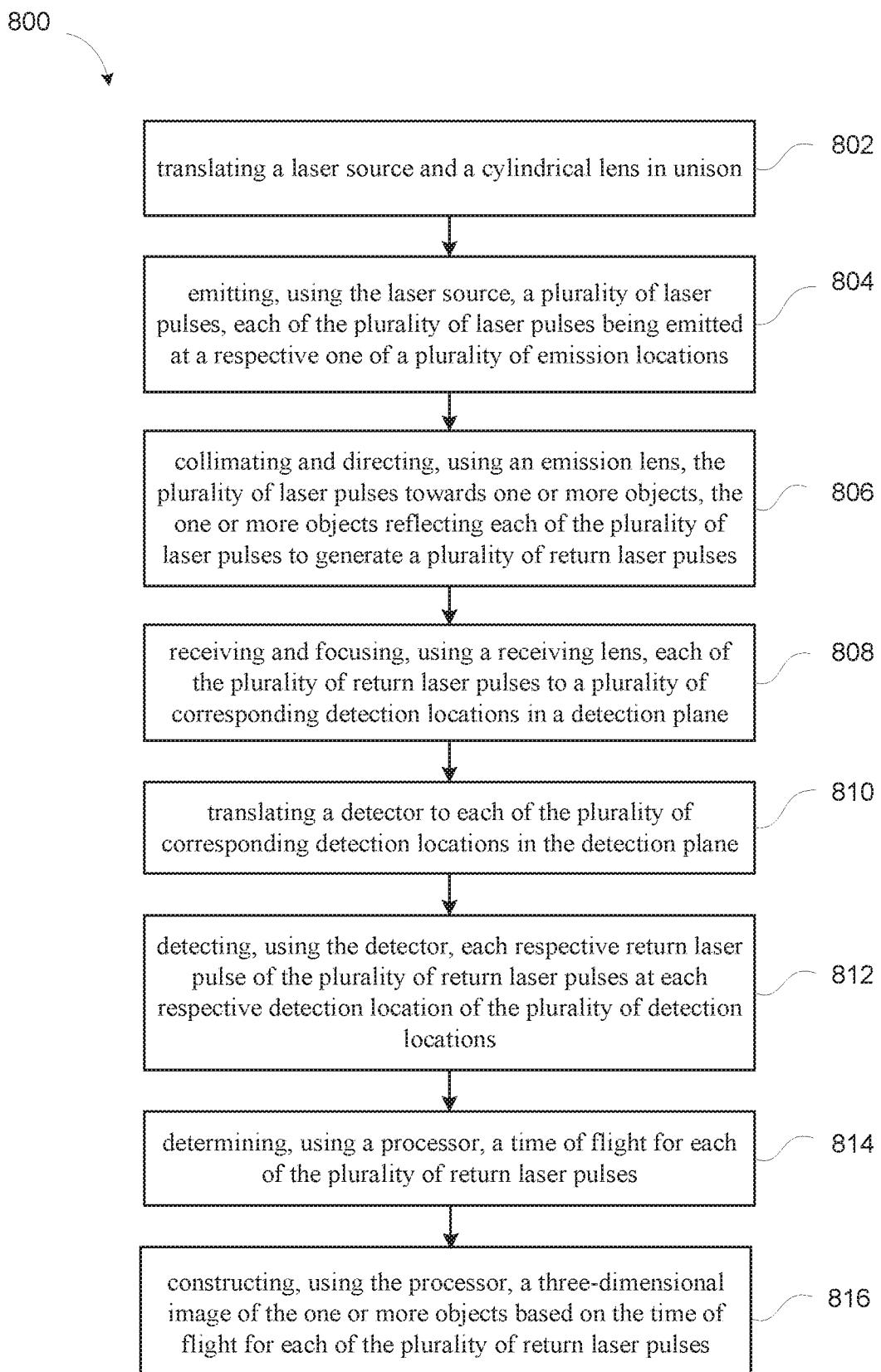
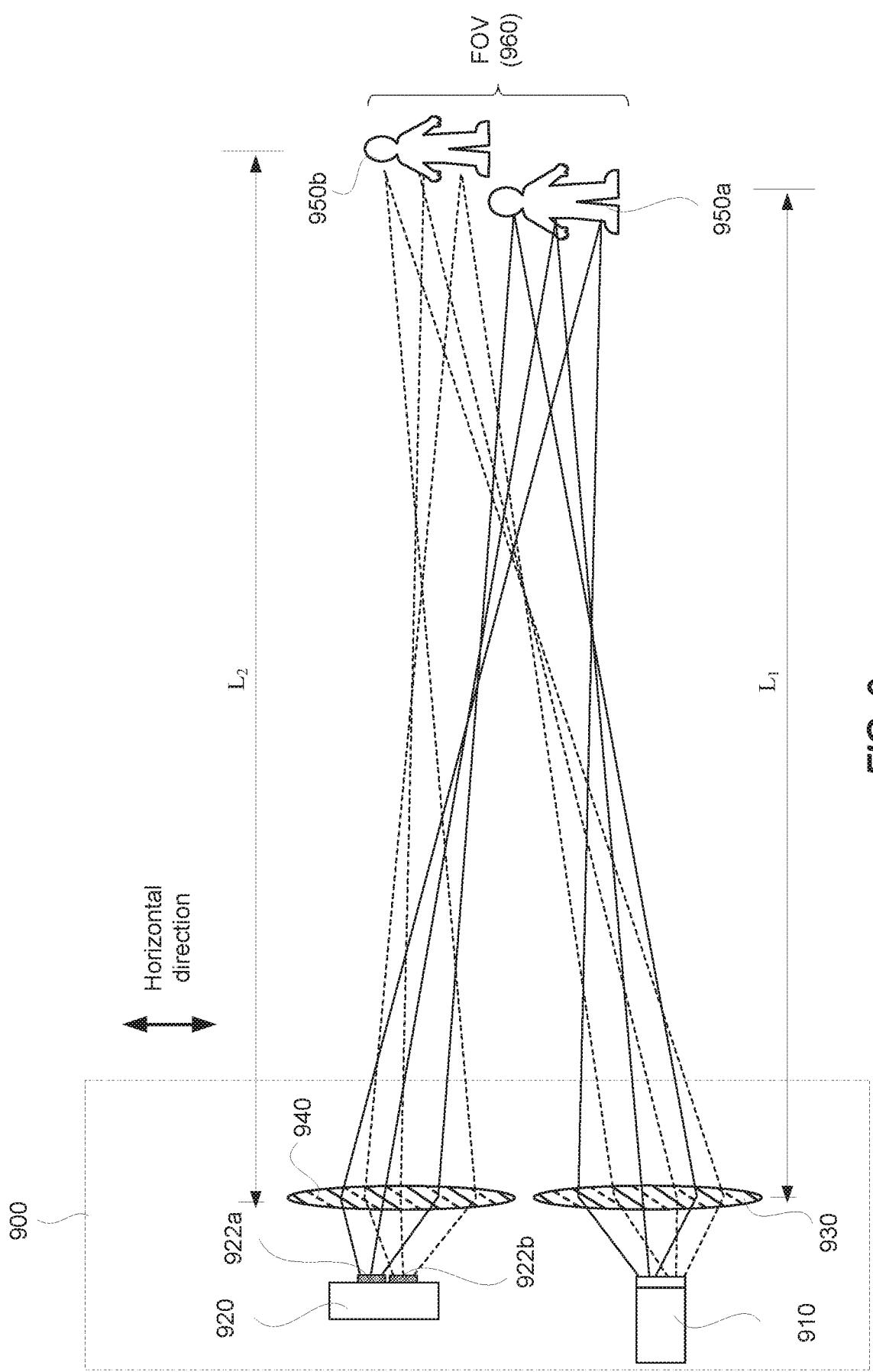


FIG. 7B

**FIG. 8**

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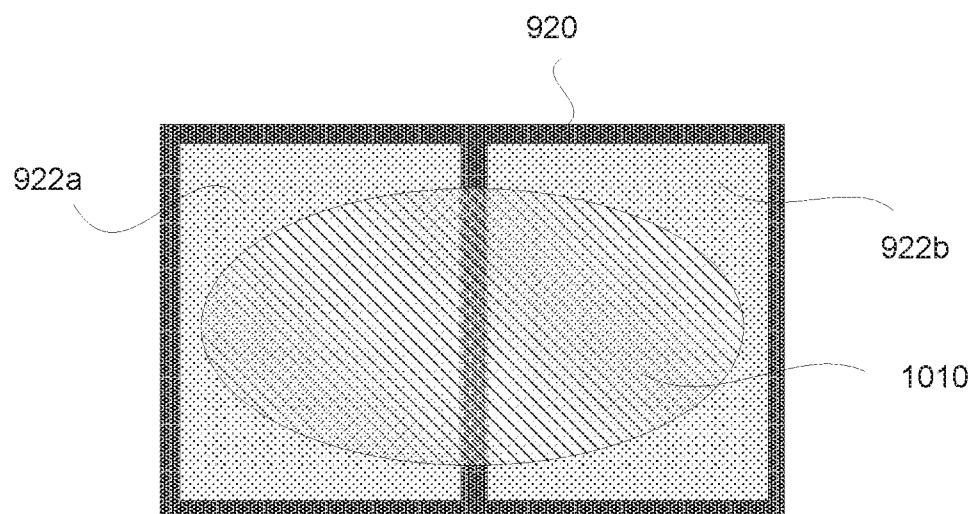


FIG. 10A

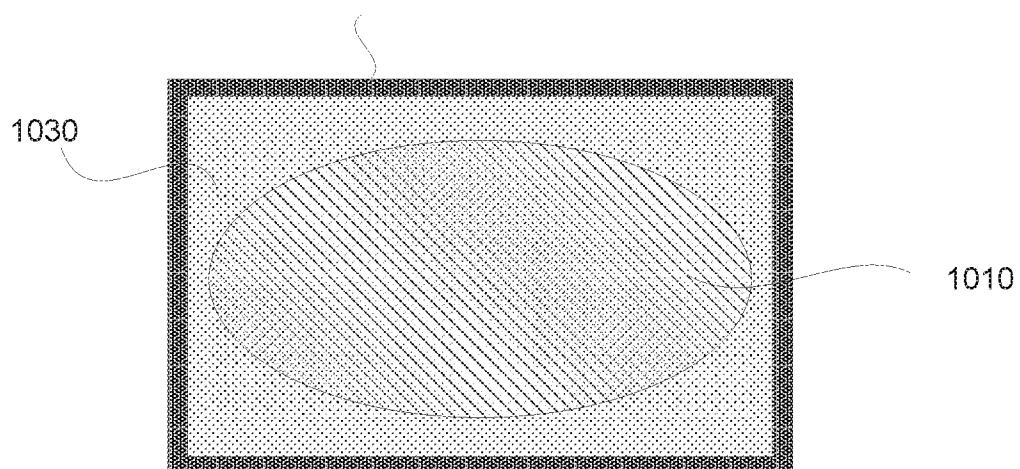
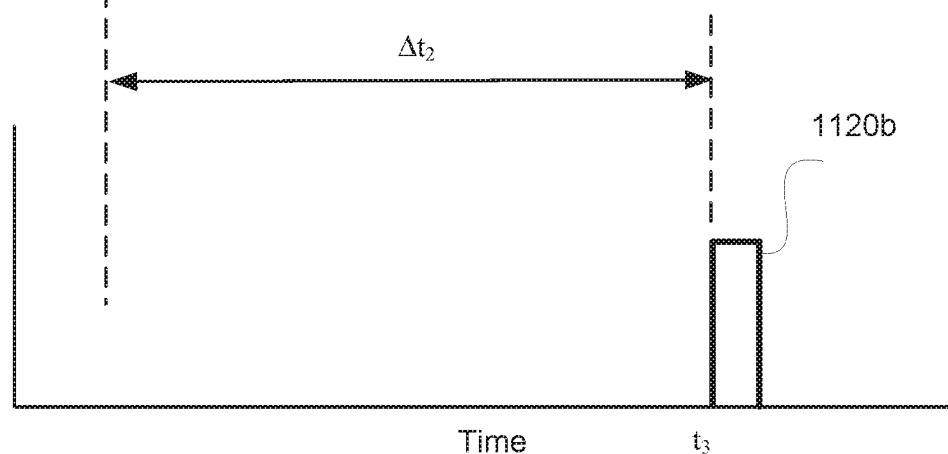
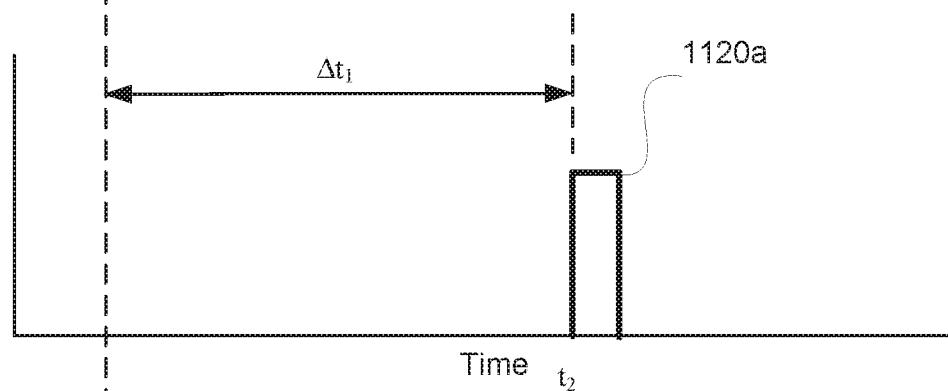
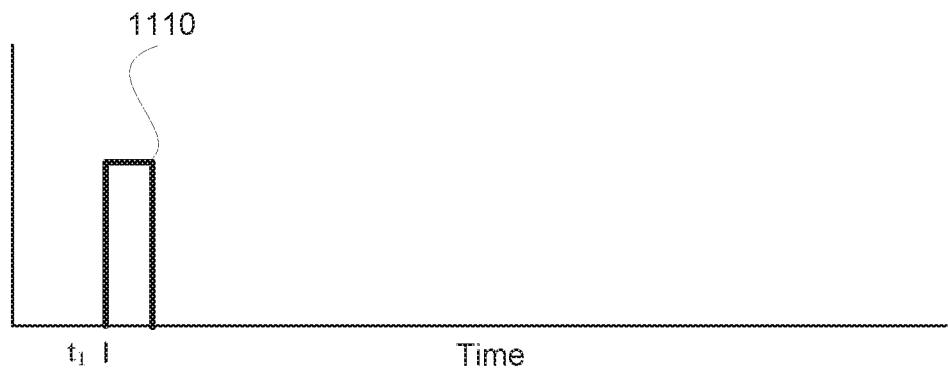


FIG. 10B



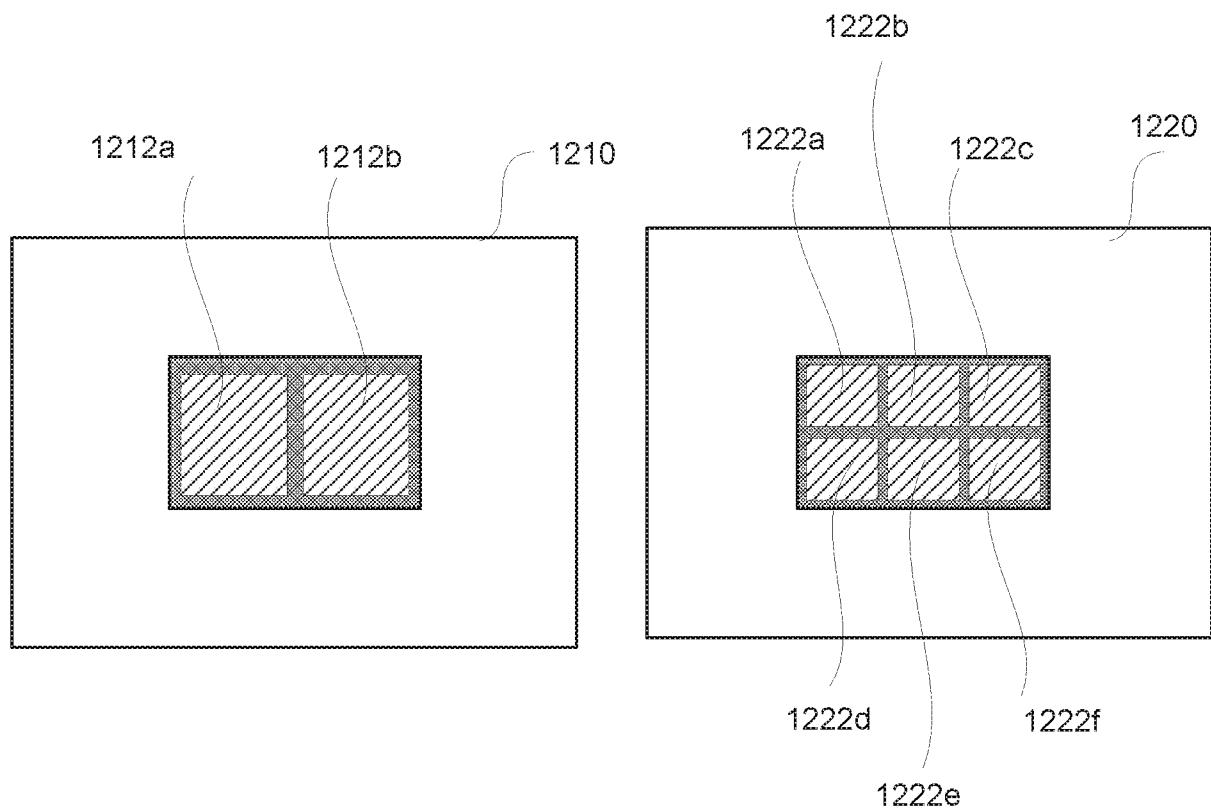


FIG. 12A

FIG. 12B

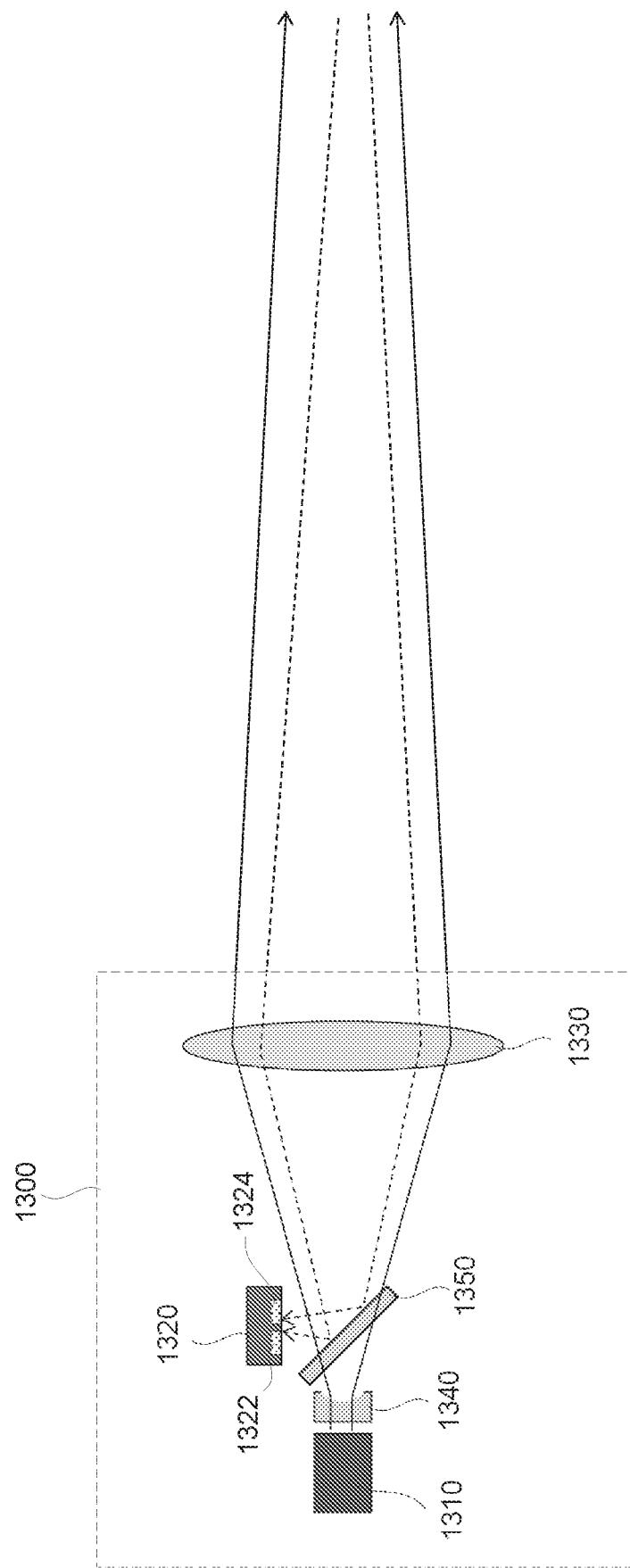


FIG. 13

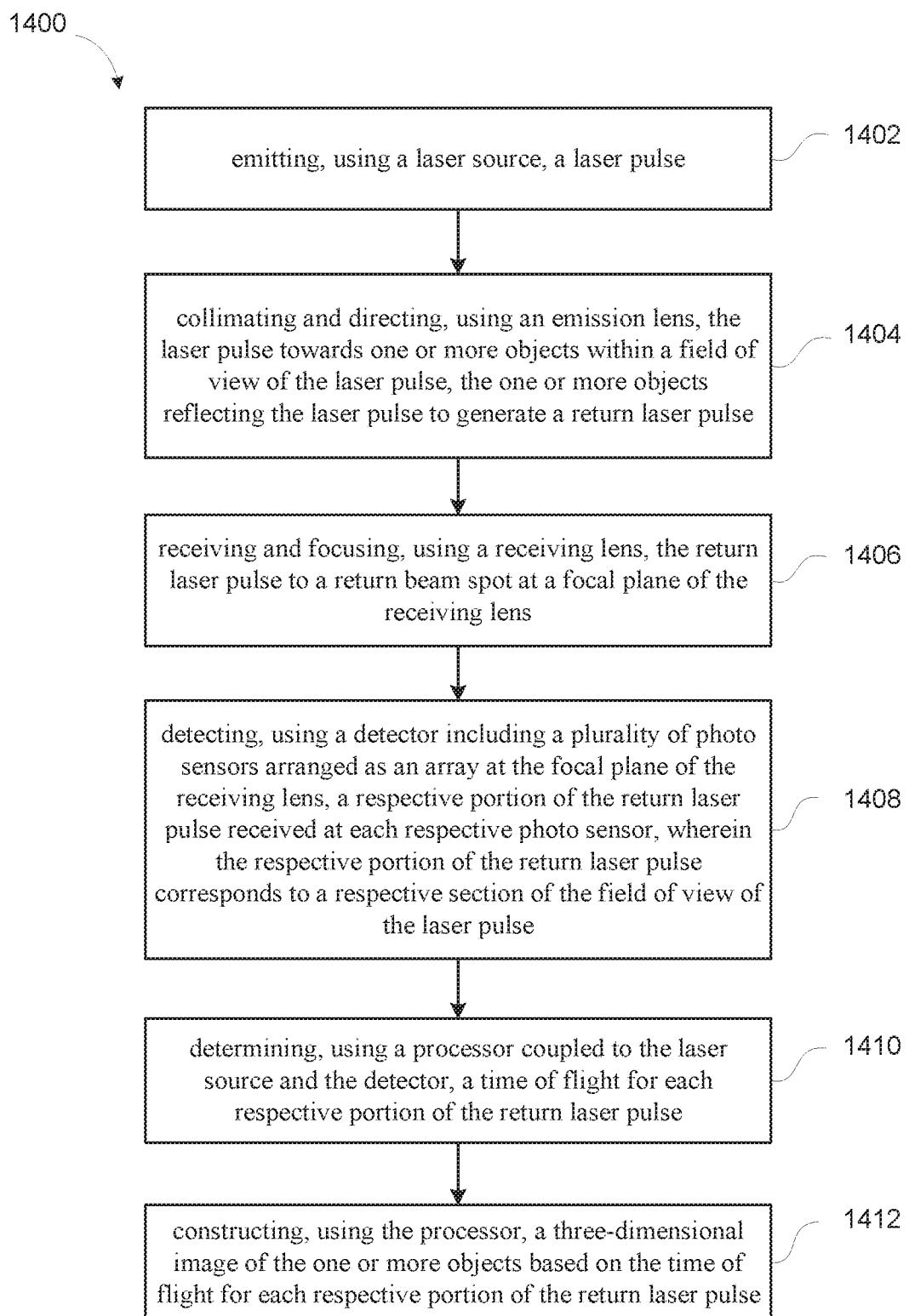


FIG. 14