PTO/AIA/14 (11-15)
Approved for use through 04/30/2017. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	103033-P001USC2-1096583
	Application Number	
Title of Invention	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS	

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.
NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

PTO/AIA/14 (11-15)
Approved for use through 04/30/2017. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	103033-P001USC2-1096583
	Application Number	
Title of Invention	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS	

Authorization or Opt-Out of Authorization to Permit Access:

When this Application Data Sheet is properly signed and filed with the application, applicant has provided written authority to permit a participating foreign intellectual property (IP) office access to the instant application-as-filed (see paragraph A in subsection 1 below) and the European Patent Office (EPO) access to any search results from the instant application (see paragraph B in subsection 1 below).

Should applicant choose not to provide an authorization identified in subsection 1 below, applicant **must opt-out** of the authorization by checking the corresponding box A or B or both in subsection 2 below.

NOTE: This section of the Application Data Sheet is **ONLY** reviewed and processed with the **INITIAL** filing of an application. After the initial filing of an application, an Application Data Sheet cannot be used to provide or rescind authorization for access by a foreign IP office(s). Instead, Form PTO/SB/39 or PTO/SB/69 must be used as appropriate.

1. Authorization to Permit Access by a Foreign Intellectual Property Office(s)

A. Priority Document Exchange (PDX) - Unless box A in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the State Intellectual Property Office of the People's Republic of China (SIPO), the World Intellectual Property Organization (WIPO), and any other foreign intellectual property office participating with the USPTO in a bilateral or multilateral priority document exchange agreement in which a foreign application claiming priority to the instant patent application is filed, access to: (1) the instant patent application-as-filed and its related bibliographic data, (2) any foreign or domestic application to which priority or benefit is claimed by the instant application and its related bibliographic data, and (3) the date of filing of this Authorization. See 37 CFR 1.14(h)(1).

B. Search Results from U.S. Application to EPO - Unless box B in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the EPO access to the bibliographic data and search results from the instant patent application when a European patent application claiming priority to the instant patent application is filed. See 37 CFR 1.14(h)(2).

The applicant is reminded that the EPO's Rule 141(1) EPC (European Patent Convention) requires applicants to submit a copy of search results from the instant application without delay in a European patent application that claims priority to the instant application.

2. Opt-Out of Authorizations to Permit Access by a Foreign Intellectual Property Office(s)

☐ A. Applicant **DOES NOT** authorize the USPTO to permit a participating foreign IP office access to the instant application-as-filed. If this box is checked, the USPTO will not be providing a participating foreign IP office with any documents and information identified in subsection 1A above.

☐ B. Applicant **DOES NOT** authorize the USPTO to transmit to the EPO any search results from the instant patent application. If this box is checked, the USPTO will not be providing the EPO with search results from the instant application.

NOTE: Once the application has published or is otherwise publicly available, the USPTO may provide access to the application in accordance with 37 CFR 1.14.

PTO/AIA/14 (11-15)
Approved for use through 04/30/2017. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	103033-P001USC2-1096583
	Application Number	
Title of Invention	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS	

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant 1

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Clear

◉ Assignee	○ Legal Representative under 35 U.S.C. 117	○ Joint Inventor
○ Person to whom the inventor is obligated to assign.	○ Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor:

If the Applicant is an Organization check here. ☒

Organization Name	Ouster, Inc.

Mailing Address Information For Applicant:

Address 1	2741 16th Street		
Address 2			
City	San Francisco	**State/Province**	CA
Country	US	Postal Code	94103
Phone Number		Fax Number	
Email Address			

Additional Applicant Data may be generated within this form by selecting the Add button.

Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

PTO/AIA/14 (11-15)
Approved for use through 04/30/2017. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	103033-P001USC2-1096583
	Application Number	
Title of Invention	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS	

Assignee 1

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication. An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

If the Assignee or Non-Applicant Assignee is an Organization check here. ☒

Organization Name	Ouster, Inc.

Mailing Address Information For Assignee including Non-Applicant Assignee:

Address 1	2741 16th Street		
Address 2			
City	San Francisco	**State/Province**	CA
Country i	US	Postal Code	94103
Phone Number		Fax Number	
Email Address			

Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button.

Signature:

NOTE: This Application Data Sheet must be signed in accordance with 37 CFR 1.33(b). **However, if this Application Data Sheet is submitted with the INITIAL filing of the application and either box A or B is not checked in subsection 2 of the "Authorization or Opt-Out of Authorization to Permit Access" section, then this form must also be signed in accordance with 37 CFR 1.14(c).**

This Application Data Sheet **must** be signed by a patent practitioner if one or more of the applicants is a **juristic entity** (e.g., corporation or association). If the applicant is two or more joint inventors, this form must be signed by a patent practitioner, **all** joint inventors who are the applicant, or one or more joint inventor-applicants who have been given power of attorney (e.g., see USPTO Form PTO/AIA/81) on behalf of **all** joint inventor-applicants.

See 37 CFR 1.4(d) for the manner of making signatures and certifications.

Signature	/ William L. Shaffer /			Date (YYYY-MM-DD)	2018-07-23
First Name	William L.	Last Name	Shaffer	Registration Number	37234

Additional Signature may be generated within this form by selecting the Add button.

PTO/AIA/14 (11-15)
Approved for use through 04/30/2017. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	103033-P001USC2-1096583
	Application Number	
Title of Invention	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS	

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent CooperationTreaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

ABSTRACT

An optical system for collecting distance information within a field is provided. The optical system may include lenses for collecting photons from a field and may include lenses for distributing photons to a field. The optical system may include lenses that collimate photons passed by an aperture, optical filters that reject normally incident light outside of the operating wavelength, and pixels that detect incident photons. The optical system may further include illumination sources that output photons at an operating wavelength.

CLAIMS

What is claimed is:

1. An optical imaging system comprising:

a bulk receiver optic having a focal plane;

an array of pixels; and

an aperture layer disposed between the bulk receiver optic and the array of pixels, the aperture layer including a plurality of discrete apertures coincident with the focal plane, wherein the aperture layer and pixel layer are arranged to form a plurality of sense channels defining a plurality of discrete, non-overlapping fields of view beyond a threshold distance in a field external to the optical imaging system, each sense channel in the plurality of sense channels including a pixel from the array of pixels and an aperture from the plurality of apertures that defines the field of view for its respective pixel, and wherein a sensing area of each pixel in the plurality of sense channels is larger than an area of its corresponding aperture in the plurality of apertures.

2. The optical imaging system of claim 1 wherein each pixel in the array of pixels comprises a plurality of subpixels distributed across its sensing area.

3. The optical imaging system of claim 2 wherein the plurality of subpixels in each pixel is a plurality of SPADs.

4. The optical imaging system of claim 1 further comprising, within each channel in the plurality of sense channels, an optical filter disposed between the bulk receiving optic and the array of pixels, the optical filter configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation while blocking radiation outside the band.

5. The optical imaging system of claim 1 further comprising:

a bulk transmitter optic; and

an illumination source comprising a plurality of lasers corresponding in number to the plurality of sense channels, each laser in the plurality of lasers configured to project a

discrete illuminating beam at an operating wavelength through the bulk transmitter optic into a field of view that is substantially the same size and geometry as a field of view defined by the bulk receiver optic and a corresponding aperture in the plurality of sense channels.

6. The optical imaging system of claim 5 wherein each laser in the plurality of lasers is a VCSEL.

7. The optical imaging system of claim 5 wherein a diameter of each discrete beam projected from the illumination source is substantially similar to a cross-section of the field of view of its respective channel at various distances from the bulk imaging optic.

8. The optical imaging system of claim 5 further comprising, within each channel in the plurality of sense channels, an optical filter disposed between the bulk receiving optic and the array of pixels, the optical filter configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation that includes the operating wavelength of the plurality of lasers to the plurality of pixels while blocking radiation outside the band.

9. The optical imaging system of claim 8 further comprising, within each channel in the plurality of sense channels, a diffuser disposed within the channel between the aperture and the pixel.

10. The optical imaging system of claim 5 wherein each laser in the plurality of lasers is a VCSEL, each pixel in the array of pixels comprises a plurality of SPADs and an optical filter is disposed between the bulk receiving optic and the array of pixels, the optical filter configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation that includes the operating wavelength of the plurality of VCSELs to the array of pixels while blocking radiation outside the band.

11. The optical imaging system of claim 1 further comprising a plurality of lenses, wherein each channel in the plurality of channels includes a lens from the plurality of lenses disposed between the aperture of the channel and its corresponding pixel.

12. The optical imaging system of claim 1 wherein adjacent apertures in the aperture layer are offset by an aperture pitch distance greater than a diameter of each aperture.

13. An optical imaging system comprising:

a bulk receiver optic having a focal plane;

an array of pixels of substantially uniform sensing area, each pixel in the array of pixels including a plurality of subpixels distributed across its sensing area; and

an aperture layer disposed between the bulk receiver optic and the array of pixels, the aperture layer including a plurality of discrete apertures of substantially uniform area formed coincident with the focal plane and stop regions interposed between adjacent apertures in the aperture layer, wherein the aperture layer and pixel layer are arranged to form a plurality of sense channels defining a plurality of discrete, non-overlapping fields of view beyond a threshold distance in a field external to the optical imaging system, each sense channel in the plurality of sense channels including an aperture from the plurality of apertures and a pixel from the array of pixels with the aperture of each channel defining the field of view for its respective pixel, and wherein the area of the aperture in each channel is smaller than the sensing area of its respective pixel.

14. The optical imaging system of claim 13 wherein the plurality of subpixels in each pixel is a plurality of SPADs.

15. The optical imaging system of claim 13 further comprising:

a bulk transmitter optic; and

an illumination source comprising a plurality of lasers corresponding in number to the plurality of sense channels, each laser in the plurality of lasers configured to project a discrete illuminating beam at an operating wavelength through the bulk transmitter optic into a field of view that is substantially the same size and geometry as a field of view defined by the bulk receiver optic and a corresponding aperture in the plurality of sense channels.

16. The optical imaging system of claim 15 wherein each aperture in the plurality of discrete apertures defines a field of view in the field coincident a discrete spot output by a corresponding laser in the plurality of lasers.

17. An optical imaging system comprising:

a bulk receiver optic having a focal plane;

an optical assembly having a plurality of sense channels defining a plurality of discrete, non-overlapping fields of view beyond a threshold distance in a field external to the bulk receiver optic, the optical assembly comprising:

an array of pixels of substantially uniform sensing area, each pixel in the array of pixels including a plurality of subpixels distributed across its sensing area;

an aperture layer disposed between the bulk receiver optic and the array of pixels, the aperture layer including a plurality of discrete apertures of substantially uniform area formed coincident with the focal plane and stop regions between adjacent apertures;

a lens layer including a plurality of lenses arranged to receive light passed through the aperture and pass the received light towards the array of pixels; and

an optical filter layer disposed between the bulk receiving optic and the array of pixels, the optical filter layer configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation while blocking radiation outside that band;

wherein each sense channel in the optical assembly includes a pixel from the array of pixels, an aperture from the aperture layer that defines the field of view for its respective pixel and has an area that is smaller than a sensing area of its respective pixel, a lens from the lens layer and a filter from the optical filter layer.

18. The optical imaging system of claim 17 wherein adjacent apertures in the aperture layer are offset by an aperture pitch distance greater than a diameter of each aperture and substantially equal to a pitch between adjacent lenses in the lens layer.

19. The optical imaging system of claim 18 wherein the optical filter layer is disposed between the lens layer and the array of pixels and wherein each lens is configured to collimate light rays passed by its respective aperture so that light rays incident on the optical filter meet the optical filter at an angle of incidence of approximately 0 degrees.

20. The optical imaging system of claim 18 further comprising:

a bulk transmitter optic; and

an illumination source comprising a plurality of lasers corresponding in number to the plurality of sense channels, each laser in the plurality of lasers configured to project a discrete illuminating beam at an operating wavelength through the bulk transmitter optic into a field of view that is substantially the same size and geometry as a field of view defined by the bulk receiver optic and a corresponding aperture in the plurality of sense channels.

21. The optical imaging system of claim 20 wherein the plurality of subpixels in each pixel is a plurality of SPADs and where the plurality of lasers in the illumination source is a plurality of VCSELs.

22. The optical imaging system of claim 21 wherein each aperture has a diameter of 200 microns or less.

23. The optical imaging system of claim 21 wherein each aperture has a diameter approaching the diffraction-limited diameter for the wavelength of light output by the plurality of lasers.

24. The optical imaging system of claim 21 wherein each aperture has a diameter less than the diffraction-limited diameter for the wavelength of light output by the plurality of lasers.

25. The optical imaging system of claim 21 wherein each aperture has a diameter matched to a dynamic range of its corresponding pixel.

26. The optical imaging system of claim 21 wherein the stop region surrounding each aperture blocks light rays reflected from a region of the surface outside the field of view of its corresponding aperture.

PATENT
Attorney Docket No.: 103033-P001USC2-1096583
Client Reference No.: P001USC2

PATENT APPLICATION

OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS

Inventors:

Angus PACALA, a citizen of United States of America, residing at 2741 16th Street, San Francisco, CA 94103

Mark FRICHTL, a citizen of United States of America, residing at San Francisco, CA

Assignee: Ouster, Inc.
2741 16th St
San Francisco, CA 94103

Entity: Small

OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. Patent Application No. 15/880,491, filed January 25, 2018, which is a continuation of U.S. Patent Application No. 15/276,532 ("the '532 application"), filed September 26, 2016; which claims the benefit of U.S. Provisional Patent Application No. 62/232,222 ("the '222 application") filed September 24, 2015. The present application is also related to U.S. Patent Application No. 15/861,330, filed on January 3, 2018, which is a continuation-in-part of the '532 application. The disclosures of the '532 and '222 applications are each incorporated by reference herein in their entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] This invention relates generally to the field of optical sensors and more specifically to a new and useful optical system for collecting distance information in the field of optical sensors.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] FIG. 1 is a schematic representation of a system.

[0004] FIG. 2 is a schematic representation in accordance with one variation of the system.

[0005] FIG. 3 is a schematic representation in accordance with one variation of the system.

[0006] FIG. 4 is a schematic representation in accordance with one variation of the system.

[0007] FIG. 5 is a schematic representation in accordance with one variation of the system.

[0008] FIG. 6 is a schematic representation in accordance with one variation of the system.

[0009] FIG. 7 is a schematic representation in accordance with one variation of the system.

[0010] FIG. 8 is a schematic representation in accordance with one variation of the system.

[0011] FIG. 9 is a flowchart representation in accordance with one variation of the system.

[0012] FIG. 10 is a schematic representation in accordance with one variation of the system.

[0013] FIG. 11 is a schematic representation in accordance with one variation of the system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0014] The following description of embodiments of the invention is not intended to limit the invention to these embodiments but rather to enable a person skilled in the art to make and use this invention. Variations, configurations, implementations, example implementations, and examples described herein are optional and are not exclusive to the variations, configurations, implementations, example implementations, and examples they describe. The invention described herein can include any and all permutations of these variations, configurations, implementations, example implementations, and examples.

1. One-Dimensional Optical System: Aperture Array

[0015] As shown in FIG. 1, a one-dimensional optical system 100 for collecting distance information within a field includes: a set of illumination sources 110 arranged along a first axis, each illumination source in the set of illumination sources 110 configured to output an illuminating beam of an operating wavelength toward a discrete spot in the field ahead of the illumination source; a bulk imaging optic 130 characterized by a focal plane opposite the field; an aperture layer 140 coincident the focal plane, defining a set of apertures 144 in a line array parallel to the first axis, and defining a stop region 146 around the set of apertures 144, each aperture in the set of apertures 144 defining a field of view in the field coincident a discrete spot output by a corresponding illumination source in the set of illumination sources 110, the stop region 146 absorbing light rays reflected from surfaces in the field outside of fields of view defined by the set of apertures 144 and passing through the bulk imaging optic 130 ; a set of lenses 150, each lens in the set of lenses 150 characterized by a second focal length, offset from the focal plane opposite the bulk imaging optic 130 by the second focal length, aligned with an aperture in the set of apertures 144, and configured to collimate light rays passed by the aperture; an optical filter 160 adjacent the set of lenses 150 opposite the aperture layer 140 and configured to pass light rays at the operating wavelength; a set of pixels 170 adjacent the optical filter 160 opposite the set of lenses 150, each pixel in the set of pixels 170 corresponding to a lens in the set of lenses 150 and including a set of subpixels arranged along a second axis non-parallel to the first axis; and a diffuser 180 interposed between the optical filter 160 and the set of pixels 170 and configured to spread collimated light output from each lens in the set of lenses 150 across a set of subpixels of a corresponding pixel in the set of pixels 170.

1.1 Applications

[0016] Generally, the one-dimensional optical system 100 (the "system") functions as an image sensor that, when rotated about an axis parallel to a column of apertures, collects three-dimensional distance data of a volume occupied by the system. Specifically, the one-dimensional optical system 100 can scan a volume to collect three-dimensional distance data that can then be reconstructed into a virtual three-dimensional representation of the volume, such as based on recorded times between transmission of illuminating beams from the illumination sources and detection of photons – likely originating from the illumination sources – incident on the set of pixels 170, based on phase-based measurements techniques, or based on any other suitable distance measurement technique. The system 100 includes: a column of offset apertures arranged behind a bulk imaging optic 130 and defining discrete fields of view in a field ahead of the bulk imaging optic 130 (that is non-overlapping fields of view beyond a threshold distance from the system); a set of illumination sources 110 that project discrete illuminating beams at an operating wavelength into (and substantially only into) the fields of view defined by the apertures; a column of lenses that collimate light rays passed by corresponding apertures; and an optical filter 160 that selectively passes a narrow band of wavelengths of light (i.e., electromagnetic radiation) including the operating wavelength; and a set of pixels 170 that detect incident photons (e.g., count incident photons, tracks times between consecutive incident photons). The system can therefore selectively project illuminating beams into a field ahead of the system according to an illumination pattern that substantially matches – in size and geometry across a range of distances from the system – the fields of view of the apertures. In particular, the illumination sources are configured to illuminate substantially only surfaces in the field ahead of the system that can be detected by pixels in the system such that minimal power output by the system (via the illumination sources) is wasted by illuminating surfaces in the field for which the pixels are blind. The system can therefore achieve a relatively high ratio of output signal (i.e., illuminating beam power) to input signal (i.e., photons passed to an incident on the pixel array). Furthermore, the set of lenses 150 can collimate light rays passed by adjacent apertures such that light rays incident on the optical filter 160 meet the optical filter 160 at an angle of incidence of approximately 0°, thereby maintaining a relatively narrow band of wavelengths of light passed by the optical filter 160 and achieving a relatively high signal-to-noise ratio ("SNR") for light rays reaching the set of pixels 170.

[0017] The system includes pixels arranged in a column and aligned with the apertures, and each pixel can be non-square in geometry (e.g., short and wide) to extend the sensing area of the system for a fixed aperture pitch and pixel column height. The system also includes a diffuser 180 that spreads light rays passed from an aperture through the optical filter 160 across the area of a corresponding pixel such that the pixel can detect incident photons across its full width and height thereby increasing the dynamic range of the system.

[0018] The system is described herein as projecting electromagnetic radiation into a field and detecting electromagnetic radiation reflected from a surface in the field back to bulk receiver optic. Terms "illumination beam," "light," "light rays," and "photons" recited herein refer to such electromagnetic radiation. The term "channel" recited herein refers to one aperture in the aperture layer 140, a corresponding lens in the set of lenses 150, and a corresponding pixel in the set of pixels 170.

1.2 Bulk Imaging Optic

[0019] The system includes a bulk imaging optic 130 characterized by a focal plane opposite the field. Generally, the bulk imaging optic 130 functions to project incident light rays from outside the system toward the focal plane where light rays incident on a stop region 146 of the aperture layer 140 are rejected (e.g., mirrored or absorbed) and where light rays incident on apertures in the aperture layer 140 are passed into a lens characterized by a focal length and offset from the focal plane by the focal length.

[0020] In one implementation, the bulk imaging optic 130 includes a converging lens, such as a bi-convex lens (shown in FIG. 2) or a plano-convex lens, characterized by a particular focal length at the operating wavelength of the system. The bulk imaging optic 130 can also include multiple discrete lens that cooperate to project light rays toward the aperture layer 140 and that are characterized by a composite focal plane opposite the field, as shown in FIG. 11. However, the bulk imaging optic 130 can be any other suitable type of lens or combination of lenses of any other type or geometry.

1.3 Aperture Layer

[0021] As shown in FIGS. 1 and 2, the system includes an aperture layer 140 coincident the focal plane, defining a set of apertures 144 in a line array parallel to the axes of the illumination sources, and defining a stop region 146 around the set of apertures 144,

wherein each aperture in the set of apertures 144 defines a field of view in the field coincident a discrete spot output by a corresponding illumination source in the set of illumination sources 110, and wherein the stop region 146 absorbs and/or reflects light rays reflected from surfaces in the field outside of fields of view defined by the set of apertures 144 and passing through the bulk imaging optic 130. Generally, the aperture layer 140 defines an array of open regions (i.e., apertures, including one aperture per lens) and closed regions ("stop regions") between adjacent opens. Each aperture in the aperture layer 140 defines a "pinhole" that defines a field of view for its corresponding sense channel and passes light rights reflected from an external surface within its field of the view into its corresponding lens, and each stop region 146 can block light rays incident on select regions of the focal plane from passing into the lens array, as shown in FIG. 6.

[0022] The aperture layer 140 includes a relatively thin opaque structure coinciding with (e.g., arranged along) the focal plane of the bulk imaging optic 130, as shown in FIGS. 1 and 2. For example, the aperture layer 140 can include a 10 micrometer-thick copper, silver, or nickel film deposited (e.g., plated) over a photocurable transparent polymer and then selectively etched to form the array of apertures. In a similar example, a reflective metalized layer or a light-absorbing photopolymer (e.g., a photopolymer mixed with a light absorbing dye) can be deposited onto a glass wafer and selectively cured with a photomask to form the aperture layer 140 and the set of apertures 144. Alternatively, the aperture layer 140 can include a discrete metallic film that is mechanically or chemically perforated to form the array of apertures, bonded to the lens array, and then installed over the bulk imaging optic 130 along the focal plane. However, the aperture layer 140 can include any other reflective (e.g., mirrored) or light-absorbing material formed in any other way to define the array of apertures along the focal plane of the bulk imaging optic 130.

[0023] In the one-dimensional optical system 100, the aperture layer 140 can define a single column of multiple discrete circular apertures of substantially uniform diameter, wherein each aperture defines an axis substantially parallel to and aligned with one lens in the lens array, as shown in FIG. 3. Adjacent apertures are offset by an aperture pitch distance greater than the aperture diameter and substantially similar to the lens pitch distance, and the aperture layer 140 defines a stop region 146 (i.e., an opaque or reflecting region) between adjacent apertures such that the apertures define discrete, non-overlapping fields of view for their corresponding sense channels. At increasingly smaller diameters up

to a diffraction-limited diameter – which is a function of wavelength of incident light and numeric aperture of the bulk imaging lens – an aperture defines a narrower field of view (i.e., a field of view of smaller diameter) and passes a sharper but lower-intensity (attenuated) signal from the bulk imaging optic 130 into its corresponding lens. The aperture layer 140 can therefore define apertures of diameter: greater than the diffraction-limited diameter for the wavelength of light output by the illumination sources (e.g., 900 nm); substantially greater than the thickness of the aperture layer 140; and less than the aperture pitch distance, which is substantially equivalent to the lens pitch distance and the pixel pitch distance. In one example, aperture layer 140 can define apertures of diameters approaching the diffraction-limited diameter to maximize geometrical selectivity of the field of view of each sense channel. Alternatively, the apertures can be of diameter less that the diffraction-limited diameter for the wavelength of light output by the illumination sources. In one example, the aperture layer 140 can define apertures of diameters matched to a power output of illumination sources in the system and to a number and photon detection capacity of subpixel photodetectors in each pixel in the set of pixels 170 to achieve a target number of photons incident on each pixel within each sampling period. In this example, each aperture can define a particular diameter that achieves target attenuation range for pixels originating from a corresponding illumination source and incident on the bulk imaging optic 130 during a sampling period. In particular, because an aperture in the aperture layer 140 attenuates a signal passed to its corresponding lens and on to its corresponding pixel, the diameter of the aperture can be matched to the dynamic range of its corresponding pixel.

[0024] In one implementation, a first aperture 141 in the aperture layer 140 passes light rays – reflected from a discrete region of a surface in the field (the field of view of the sense channel) ahead of the bulk imaging optic 130 – into its corresponding lens; a stop region 146 interposed between the first aperture 141 and adjacent apertures in the aperture layer 140 blocks light rays – reflected from a region of the surface outside of the field of view of the first aperture 141 – from passing into the lens corresponding to the first aperture 141. In the one-dimensional optical system 100, the aperture layer 140 therefore defines a column of apertures that define multiple discrete, non-overlapping fields of view of substantially infinite depth of field, as shown in FIG. 2.

[0025] In this implementation, a first aperture 141 in the aperture layer 140 defines a field of view that is distinct and that does not intersect a field of view defined by another aperture in the aperture layer 140, as shown in FIG. 2. The set of illumination sources 110 includes a first illumination source 111 paired with the first aperture 141 and configured to project an illuminating beam substantially aligned with (i.e., overlapping) the field of view of the first aperture 141 in the field ahead of the bulk imaging optic 130. Furthermore, the first illumination source 111 and a bulk transmitting optic 120 can cooperate to project an illuminating beam of a cross-section substantially similar to (and slightly larger than) the cross section of the field of view of the first aperture 141 as various distances from the bulk imaging optic 130. Therefore light output by the first illumination source 111 – paired with the first aperture 141 – and projected into the field of view of the first aperture 141 can remain substantially outside the fields of view of other apertures in the aperture layer 140.

[0026] Generally, photons projected into the field by the first illumination source 111 illuminate a particular region of a surface (or multiple surfaces) in the field within the field of view of the first sense channel and are reflected (e.g., scattered) by the surface(s); at least some of these photons reflected by the particular region of a surface may reach the bulk imaging optic 130, which directs these photons toward the focal plane. Because these photons were reflected by a region of a surface within the field of view of the first aperture 141, the bulk imaging optic 130 may project these photons into the first aperture 141, and the first aperture 141 may pass these photons into the first lens 151 (or a subset of these photons incident at an angle relative to the axis of the first aperture 141 below a threshold angle). However, because a second aperture 142 in the aperture layer 140 is offset from the first aperture 141 and because the particular region of the surface in the field illuminated via the first illumination source 111 does not (substantially) coincide with the field of view of the second aperture 142, photons reflected by the particular region of the surface and reaching the bulk imaging optic 130 are projected into the second aperture 142 and passed to a second lens 152 behind the second aperture 142, and vice versa, as shown in FIG. 2. Furthermore, a stop region 146 between the first and second apertures 142 can block photons directed toward the focal plane between the first and second apertures 142 reflected by the bulk imaging optic 130, thereby reducing crosstalk between the first and second sense channels.

[0027] For a first aperture 141 in the aperture layer 140 paired with a first illumination source 111 in the set of illumination sources 110, the first aperture 141 in the aperture layer 140 defines a first field of view and passes – into the first lens 151 – incident light rays originating at or reflected from a surface in the field coinciding with the first field of view. Because the first illumination source 111 projects an illuminating beam that is substantially coincident (and substantially the same size as or minimally larger than) the field of view defined by the first aperture 141 (as shown in FIG. 4), a signal passed into the first lens 151 by the first aperture 141 in the aperture layer 140 can exhibit a relatively high ratio of light rays originating from the first illumination source 111 to light rays originating from other illumination sources in the system. Generally, because various illumination sources in the system may output illuminating beams at different frequencies, duty cycles, and/or power levels, etc. at a particular time during operation, light rays passed from the bulk imaging optic 130 into a first pixel 171 in the set of pixels 170 but originating from an illumination source other than the first illumination source 111 paired with the first pixel 171 constitute noise at the first pixel 171. Though the relatively small diameters of apertures in the aperture layer 140 may attenuate a total light signal passed from the bulk imaging optic 130 into the set of lenses 150, each aperture in the aperture layer 140 may pass a relatively high proportion of photons originating from its corresponding illumination source than from other illumination sources in the system; that is, due to the geometry of a particular aperture and its corresponding illumination source, a particular aperture may pass a signal exhibiting a relatively high SNR to its corresponding lens and thus into its corresponding pixel. Furthermore, at smaller aperture diameters in the aperture layer 140 – and therefore smaller fields of view of corresponding channels – the system can pass less noise from solar radiation or other ambient light sources to the set of pixels 170.

[0028] In one variation, the system includes a second aperture layer interposed between the lens array and the optical filter 160, wherein the second aperture layer defines a second set of apertures 144, each aligned with a corresponding lens in the set of lenses 150, as described above. In this variation, an aperture in the second aperture layer 140 can absorb or reflect errant light rays passed by a corresponding lens, as described above, to further reduce crosstalk between channels, thereby improving SNR within the system. Similarly, the system can additionally or alternatively include a third aperture layer interposed between the optical filter 160 and the diffuser(s) 180, wherein the third aperture layer

defines a third set of apertures 144, each aligned with a corresponding lens in the set of lenses 150, as described above. In this variation, an aperture in the third aperture layer can absorb or reflect errant light rays passed by the light filter, as described above, to again reduce crosstalk between channels, thereby improving SNR within the system.

1.4 Lens Array

[0029] The system includes a set of lenses 150, wherein each lens in the set of lenses 150 is characterized by a second focal length, is offset from the focal plane opposite the bulk imaging optic 130 by the second focal length, is aligned with a corresponding aperture in the set of apertures 144, and is configured to collimate light rays passed by the corresponding aperture. Generally, a lens in the set of lenses 150 functions to collimate lights rays passed by its corresponding aperture and to pass these collimated light rays into the optical filter 160.

[0030] In the one-dimensional optical system 100, the lenses are arranged in a single column, and adjacent lenses are offset by a uniform lens pitch distance (i.e., a center-to-center-distance between adjacent pixels), as shown in FIG. 3. The set of lenses 150 is interposed between the aperture layer and the optical filter 160. In particular, each lens can include a converging lens characterized by a second focal length and can be offset from the focal plane of the bulk imaging optic 130 – opposite the bulk imaging optic 130 – by the second focal length to preserve the aperture of the bulk imaging optic 130 and to collimate light incident on the bulk imaging optic 130 and passed by a corresponding aperture. Each lens in the set of lens can be characterized by a relatively short focal length (i.e., less than a focal length of the bulk imaging optic 130) and a relatively large marginal ray angle (e.g., a relatively high numeric aperture lens) such that the lens can capture highly-angled light rays projected toward the lens by the extent of the bulk imaging optic 130. That is, each lens in the set of lens can be characterized by a ray cone substantially matched to a ray cone of the bulk imaging optic 130.

[0031] Lenses in the set of lenses 150 can be substantially similar. A lens in the set of lenses 150 is configured to collimate light rays focused into its corresponding aperture by the bulk imaging optic 130. For example, a lens in the set of lenses 150 can include a bi-convex or plano-convex lens characterized by a focal length selected based on the size (e.g., diameter) of its corresponding aperture and the operating wavelength of the system. In this

example, the focal length (f) of a lens in the set of lenses 150 can be calculated according to the formula:

$$f = \frac{d^2}{2\lambda}$$

where d is the diameter of the corresponding aperture in the aperture layer and λ is the operating wavelength of light output by the illumination source (e.g., 900 nm). The geometry of a lens in the set of lenses 150 can therefore be matched to the geometry of a corresponding aperture in the aperture layer such that the lens passes a substantially sharp image of light rays – at or near the operating wavelength – into the optical filter 160 and thus on to the pixel array.

[0032] However, the set of lenses 150 can include lenses of any other geometry and arranged in any other way adjacent the aperture layer.

1.5 Optical Filter

[0033] As shown in FIG. 3, the system includes an optical filter 160 adjacent the set of lenses 150 opposite the aperture layer and configured to pass light rays at the operating wavelength. Generally, the optical filter 160 receives electromagnetic radiation across a spectrum from the set of lenses 150, passes a relatively narrow band of electromagnetic radiation – including radiation at the operating wavelength – to the pixel array, and blocks electromagnetic radiation outside of the band. In particular, electromagnetic radiation other than electromagnetic radiation output by the illumination source – such as ambient light – incident on a pixel in the set of pixels 170 constitutes noise in the system. The optical filter 160 therefore functions to reject electromagnetic radiation outside of the operating wavelength or, more pragmatically, outside of a narrow wavelength band, thereby reducing noise in the system and increasing SNR.

[0034] In one implementation, the optical filter 160 includes an optical bandpass filter that passes a narrow band of electromagnetic radiation substantially centered at the operating wavelength of the system. In one example, the illumination sources output light (predominantly) at an operating wavelength of 900 nm, and the optical filter 160 is configured to pass light between 899.95 nm and 900.05 nm and to block light outside of this band.

[0035] The optical filter 160 may selectively pass and reject wavelengths of light as a function of angle of incidence on the optical filter 160. Generally, optical bandpass filters may pass wavelengths of light inversely proportional to their angle of incidence on the light optical bandpass filter. For example, for an optical filter 160 including a 0.5 nm-wide optical bandpass filter, the optical filter 160 may pass over 95% of electromagnetic radiation over a sharp band from 899.75 nm to 900.25 nm and reject approximately 100% of electromagnetic radiation below 899.70 nm and above 900.30 nm for light rays incident on the optical filter 160 at an angle of incidence of approximately 0°. However, in this example, the optical filter 160 may pass over 95% of electromagnetic radiation over a narrow band from 899.5 nm to 900.00 nm and reject approximately 100% of electromagnetic radiation over a much wider band below 899.50 nm and above 900.30 nm for light rays incident on the optical filter 160 at an angle of incidence of approximately 15°. Therefore, the incidence plane of the optical filter 160 can be substantially normal to the axes of the lenses, and the set of lenses 150 can collimate light rays received through a corresponding aperture and output these light rays substantially normal to the incidence plane of the optical filter 160 (i.e., at an angle of incidence of approximately 0° on the optical filter). Specifically, the set of lenses 150 can output light rays toward the optical filter 160 at angles of incidence approximating 0° such that substantially all electromagnetic radiation passed by the optical filter 160 is at or very near the operating wavelength of the system.

[0036] In the one-dimensional optical system 100, the system can include a single optical filter 160 that spans the column of lens in the set of lenses 150. Alternatively, the system can include multiple optical filters 160, each adjacent a single lens or a subset of lenses in the set of lenses 150. However, the optical filter 160 can define any other geometry and can function in any other way to pass only a limited band of wavelengths of light.

1.6 Pixel Array and Diffuser

[0037] The system includes a set of pixels 170 adjacent the optical filter 160 opposite the set of lenses 150, each pixel in the set of pixels 170 corresponding to a lens in the set of lenses 150 and including a set of subpixels arranged along a second axis non-parallel to the first axis. Generally, the set of pixels 170 are offset from the optical filter 160 opposite the set of lenses 150, and each pixel in the set of pixels 170 functions to output a single signal or stream of signals corresponding to the count of photons incident on the pixel within one

or more sampling periods, wherein each sampling period may be picoseconds, nanoseconds, microseconds, or milliseconds in duration.

[0038] The system also includes a diffuser 180 interposed between the optical filter 160 and the set of pixels 170 and configured to spread collimated light output from each lens in the set of lenses 150 across a set of subpixels of a single corresponding pixel in the set of pixels 170. Generally, for each lens in the set of lenses 150, the diffuser 180 functions to spread light rays – previously collimated by the lens and passed by the optical filter 160 – across the width and height of a sensing area within a corresponding pixel. The diffuser 180 can define a single optic element spanning the set of lenses 150, or the diffuser 180 can include multiple discrete optical elements, such as including one optical diffuser element aligned with each channel in the system.

[0039] In one implementation, a first pixel 171 in the set of pixels 170 includes an array of single-photon avalanche diode detectors (hereinafter "SPADs"), and the diffuser 180 spreads lights rays – previously passed by a corresponding first aperture 141, collimated by a corresponding first lens 151, and passed by the optical filter 160 – across the area of the first pixel 171, as shown in FIGS. 3, 5, and 6. Generally, adjacent apertures can be aligned and offset vertically by an aperture pitch distance, adjacent lenses can be aligned and offset vertically by a lens pitch distance substantially identical to the aperture pitch distance, and adjacent pixels can be aligned and offset vertically by a pixel pitch distance substantially identical to the lens and aperture pitch distances. However, the pixel pitch distance may accommodate only a relatively small number of (e.g., two) vertically-stacked SPADs. Each pixel in the set of pixels 170 can therefore define an aspect ratio greater than 1:1, and the diffuser 180 can spread light rays passed by the optical filter 160 according to the geometry of a corresponding pixel in order to accommodate a larger sensing area per pixel.

[0040] In one example, each pixel in the set of pixels 170 is arranged on an image sensor, and a first pixel 171 in the set of pixels 170 includes a single row of 16 SPADs spaced along a lateral axis perpendicular to a vertical axis bisecting the column of apertures and lenses. In this example, the height of a single SPAD in the first pixel 171 can be less than the height (e.g., diameter) of the first lens 151, but the total length of the 16 SPADs can be greater than the width (e.g., diameter) of the first lens 151; the diffuser 180 can therefore converge light rays output from the first lens 151 to a height corresponding to the height of a SPAD at the plane of the first pixel 171 and can diverge light rays output from the first

lens 151 to a width corresponding to the width of the 16 SPADs at the plane of the first pixel 171. In this example, the remaining pixels in the set of pixels 170 can include similar rows of SPADs, and the diffuser 180 can similarly converge and diverge light rays passed by corresponding apertures onto corresponding pixels.

[0041] In the foregoing example, the aperture layer can include a column of 16 like apertures, the set of lenses 150 can include a column of 16 like lenses arranged behind the aperture layer, and the set of pixels 170 can include a set of 16 like pixels – each including a similar array of SPADs – arranged behind the set of lenses 150. For a 6.4 mm-wide, 6.4 mm-tall image sensor, each pixel can include a single row of 16 SPADs, wherein each SPAD is electrically coupled to a remote analog front-end processing electronics/digital processing electronics circuit 240. Each SPAD can be arranged in a 400 µm-wide, 400 µm-tall SPAD area and can define an active sensing area approaching 400 µm in diameter. Adjacent SPADs can be offset by a SPAD pitch distance of 400 µm. In this example, the aperture pitch distance along the vertical column of apertures, the lens pitch distance along the vertical column of lenses, and the pixel pitch distance along the vertical column of pixels can each be approximately 400 µm accordingly. For the first sense channel in the system (i.e., the first aperture 141, the first lens 151, and the first pixel 171, etc.), a first diffuser 180 can diverge a cylindrical column of light rays passed from the first lens 151 through the optical filter 160 – such as a column of light approximately 100 µm in diameter for an aperture layer aspect ratio of 1:4 – to a height of approximately 400 µm aligned vertically with the row of SPADs in the first pixel 171. The first diffuser can similarly diverge the cylindrical column of light rays passed from the first lens 151 through the optical filter 160 to a width of approximately 6.4 µm centered horizontally across the row of SPADs in the first pixel 171. Other diffusers 180 in the system can similarly diverge (or converge) collimated light passed by corresponding lenses across corresponding pixels in the set of pixels 170. Therefore, in this example, by connecting each SPAD (or each pixel) to a remote analog front-end processing electronics/digital processing electronics circuit 240 and by incorporating diffusers 180 that spread light passed by the optical filter 160 across the breadths and heights of corresponding pixels, the system can achieve a relatively high sensing area fill factor across the imaging sensor.

[0042] Therefore, in the one-dimensional optical system 100, pixels in the set of pixels 170 can include an array of multiple SPADS arranged in aspect ratio exceeding 1:1, and the

diffuser 180 can spread light rays across corresponding non-square pixels that enables a relatively large numbers of SPADs to be tiled across a single pixel to achieve a greater dynamic range across the image sensor than an image sensor with a single SPAD per pixel, as shown in FIG. 3. In particular, by incorporating multiple SPADs per pixel (i.e., per sense channel), a first sense channel in the system can detect multiple incident photons – originating from a surface in the field bound by a field of view defined by the first aperture 141 – within the span of the dead time characteristic of the SPADs. The first sense channel can therefore detect a "brighter" surface in its field of view. Additionally or alternatively, the first pixel 171 in the first sense channel can be sampled faster than the dead time characteristic of SPADs in the first pixel 171 because, though a first subset of SPADs in the first pixel 171 may be down (or "dead") during a first sampling period due to collection of incident photons during the first sampling period, other SPADs in the first pixel 171 remain on (or "alive") and can therefore collect incident photons during a subsequent sampling period. Furthermore, by incorporating pixels characterized by relatively high aspect ratios of photodetectors, the image sensor can include pixels offset by a relatively small pixel pitch, but the system 100 can still achieve a relatively high dynamic range pixel.

[0043] However, pixels in the set of pixels 170 can include any other number of SPADs arranged in any other arrays, such as in a 64-by-1 grid array (as described above), in a 32-by-2 grid array, or in a 16-by-4 grid array, and the diffuser 180 can converge and/or diverge collimated light rays onto corresponding pixels accordingly in any other suitable way. Furthermore, rather than (or in addition to) SPADs, each pixel in the set of pixels 170 can include one or more linear avalanche photodiodes, Geiger mode avalanche photodiodes, photomultipliers, resonant cavity photodiodes, QUANTUM DOT detectors, or other types of photodetectors arranged as described above, and the diffuser(s) 180 can similarly converge and diverge signals passed by the optical filter(s) 160 across corresponding pixels, as described herein.

1.7 Illumination Sources

[0044] The system includes a set of illumination sources 110 arranged along a first axis, each illumination source in the set of illumination sources 110 configured to output an illuminating beam of an operating wavelength toward a discrete spot in a field ahead of the illumination source. Generally, each illumination source functions to output an illuminating

beam coincident a field of view defined by a corresponding aperture in the set of apertures 144, as shown in FIGS. 1 and 2.

[0045] In one implementation, the set of illumination sources 110 includes a bulk transmitter optic and one discrete emitter per sense channel. For example, the set of illumination sources 110 can include a monolithic VCSEL arrays including a set of discrete emitters. In this implementation, the bulk transmitter optic can be substantially identical to the bulk imaging optic 130 in material, geometry (e.g., focal length), thermal isolation, etc., and the bulk transmitter optic is adjacent and offset laterally and/or vertically from the bulk imaging optic 130. In a first example, set of illumination sources 110 includes a laser array including discrete emitters arranged in a column with adjacent emitters offset by an emitter pitch distance substantially identical to the aperture pitch distance. In this first example, each emitter outputs an illuminating beam of diameter substantially identical to or slightly greater than the diameter of a corresponding aperture in the apertures layer, and the column of emitters is arranged along the focal plane of the bulk transmitter optic such that each illuminating beam projected from the bulk transmitter optic into the field intersects and is of substantially the same size and geometry as the field of view of the corresponding sense channel, as shown in FIG. 4. Therefore, substantially all power output by each emitter in the set of illumination sources 110 can be projected into the field of view of its corresponding sense channel with relatively minimal power wasted illuminating surfaces in the field outside of the fields of view of the sense channels.

[0046] In a second example, the discrete emitters are similarly arranged in a column with adjacent emitters offset by an emitter pitch distance twice the aperture pitch distance, as shown in FIG. 2. In this second example, each emitter is characterized by an illuminating active area (or aperture) of diameter approximately (or slightly greater than) twice the diameter of a corresponding aperture in the apertures layer, and the column of emitters is offset behind the bulk transmitter optic by twice the focal length of the bulk transmitter optic such that each illuminating beam projected from the bulk transmitter optic into the field intersects and is of substantially the same size and geometry as the field of view of the corresponding sense channel, as described above. Furthermore, for the same illumination beam power density, an illuminating beam output by an emitter in this second example may contain four times the power of an illuminating beam output by an emitter in the first example described above. The system can therefore include a set of emitter arranged

according to an emitter pitch distance, configured to output illuminating beams of diameter, and offset behind the bulk transmitter optic by an offset distance as a function of a scale factor (e.g., 2.0 or 3.0) and 1) the aperture pitch distance in the aperture layer, 2) the diameter of apertures in the aperture layer, and 3) the focal length of bulk transmitter optic, respectively. The system can therefore include an illuminating subsystem that is proportionally larger than a corresponding receiver subsystem to achieve greater total output illumination power within the same beam angles and fields of view of corresponding channels in the receiver subsystem.

[0047] The system can also include multiple discrete sets of illumination sources, each set of illumination sources 110 paired with a discrete bulk transmitter optic adjacent the bulk imaging optic 130. For example, the system can include a first bulk transmitter optic, a second bulk transmitter optic, and a third bulk transmitter optic patterned radially about the bulk imaging optic 130 at a uniform radial distance from the center of the bulk imaging optic 130 and spaced apart by an angular distance of 120°. In this example, the system can include a laser array with one emitter – as described above – behind each of the first, second, and third bulk transmitter optics. Each discrete laser array and its corresponding bulk transmitter optic can thus project a set of illuminating beams into the fields of view of defined by corresponding in the apertures in the aperture layer. Therefore, in this example, the three discrete laser arrays and the three corresponding bulk transmitter optics can cooperate to project three times the power onto the fields of view of the sense channels in the system, as compared to a single laser array and one bulk transmitter optic. Additionally or alternatively, the system can include multiple discrete layer arrays and bulk transmitter optics to both: 1) achieve a target illumination power output into the field of view of each sensing channel in the receiver subsystem with multiple lower-power emitters per sensing channel; and 2) distribute optical energy over a larger area in the near-field to achieve an optical energy density less than a threshold allowable optical energy density for the human eye.

[0048] However, the system can include any other number and configuration of illumination source sets and bulk transmitter optics configured to illuminate fields of view defined by the sense channels. The set of illumination sources 110 can also include any other suitable type of optical transmitter, such as a 1x16 optical splitter powered by a single

laser diode, a side-emitting laser diode array, an LED array, or a quantum dot LED array, etc.

1.8 Fabrication

[0049] In one implementation, the bulk receiver lens, the aperture layer, the set of lenses 150, the optical filter 160, and the diffuser 180 are fabricated and then aligned with and mounted onto an image sensor. For example, the optical filter 160 can be fabricated by coating a fused silica substrate. Photoactive optical polymer can then be deposited over the optical filter 160, and a lens mold can be placed over the photoactive optical polymer and a UV light source activated to cure the photoactive optical polymer in the form of lenses patterned across the optical filter 160. Standoffs can be similarly molded or formed across the optical filter 160 via photolithography techniques, and an aperture layer defined by a selectively-cured, metallized glass wafer can then be bonded or otherwise mounted to the standoffs to form the aperture layer. The assembly can then be inverted, and a set of discrete diffusers and standoffs can be similarly fabricated across the opposite side of the optical filter 160. A discrete image sensor can then be aligned with and bonded to the standoffs, and a bulk imaging optic 130 can be similarly mounted over the aperture layer.

[0050] Alternatively, photolithography and wafer level bonding techniques can be implemented to fabricate the bulk imaging optics, the aperture layer, the set of lenses 150, the optical filter 160, and the diffuser 180 directly on to the un-diced semiconductor wafer containing the detector chips in order to simplify manufacturing, reduce cost, and reduce optical stack height for decreased pixel crosstalk.

2. One-Dimensional Optical System: Lens Tube

[0051] One variation of the system includes: a set of illumination sources 110 arranged along a first axis, each illumination source in the set of illumination sources 110 configured to output an illuminating beam of an operating wavelength toward a discrete spot in a field ahead of the illumination source; a bulk imaging optic 130 characterized by a focal plane opposite the field; a set of lens tubes 210 arranged in a line array parallel to the first axis, each lens tube in the set of lens tubes 210 including: a lens characterized by a focal length, offset from the focal plane by the focal length, and configured to collimate light rays reflected into the bulk imaging optic 130 from a discrete spot in the field illuminated by a corresponding illumination source in the set of optics into the bulk imaging optic 130; and a

cylindrical wall 218 extending from the lens opposite the focal plane, defining a long axis substantially perpendicular to the first axis, and configured to absorb incident light rays reflected into the bulk imaging optic 130 from a region in the field outside the discrete spot illuminated by the corresponding illumination source. In this variation, the system also includes: an optical filter 160 adjacent the set of lens tubes 210 opposite the focal plane and configured to pass light rays at the operating wavelength; a set of pixels 170 adjacent the optical filter 160 opposite the set of lenses 150, each pixel in the set of pixels 170 corresponding to a lens in the set of lenses 150 and including a set of subpixels aligned along a third axis perpendicular to the first axis; and a diffuser 180 interposed between the optical filter 160 and the set of pixels 170 and configured to spread collimated light output from each lens in the set of lenses 150 across a set of subpixels of a corresponding pixel in the set of pixels 170.

[0052] Generally, in this variation, the system includes a lens tube in replacement of (or in addition to) each aperture and lens pair described above. In this variation, each lens tube can be characterized by a second (short) focal length and can be offset from the focal plane of the bulk imaging optic 130 by the second focal length to preserve the aperture of the bulk imaging optic 130 and to collimate incident light received from the bulk imaging optic 130, as described above and as shown in FIGS. 5 and 7.

[0053] Each lens tube also defines an opaque cylindrical wall 218 defining an axis normal to the incidence plane of the adjacent optical filter 160 and configured to absorb incident light rays, as shown in FIG. 5. Generally, at greater axial lengths, the cylindrical wall 218 of a lens tube may absorb light rays passing through the lens tube at shallower angles to the axis of the lens tube, thereby reducing the field of view of the lens tube (which may be similar to decreasing the diameter of an aperture in the aperture layer up to the diffraction-limited diameter, as described above) and yielding an output signal of collimated light rays nearer to perpendicular to the incidence plane of the optical filter 160. Each lens tube can therefore define an elongated cylindrical wall 218 of length sufficient to achieve a target field of view and to pass collimated light rays at maximum angles to the axis of the lens tube less than a threshold angle. In this variation, a lens tube can thus function as an aperture-sense pair described above to define a narrow field of view and to output substantially collimated light to the adjacent optical filter 160.

[0054] The cylindrical wall 218 of a lens tube can define a coarse or patterned opaque interface about a transparent (or translucent) lens material, as shown in FIG. 5, to increase absorption and decrease reflection of light rays incident on the cylindrical wall 218. Each lens tube (and each lens described above) can also be coated with an anti-reflective coating.

[0055] As shown in FIG. 9, in this variation, the set of lens tubes 210 can be fabricated by implementing photolithography techniques to pattern a photoactive optical polymer (e.g., SU8) onto the optical filter 160 (e.g., on a silicon wafer defining the optical filter). A light-absorbing polymer can then be poured between the lens tubes and cured. A set of lenses 150 can then be fabricated (e.g., molded) separately and then bonded over the lens tubes. Alternatively, lenses can be fabricated directly onto the lens tubes by photolithography techniques. Yet alternatively, a mold for lenses can be cast directly onto the lens tubes by injecting polymer into a mold arranged over the lens tubes. A singular diffuser 180 or multiple discrete diffusers 180 can be similarly fabricated and/or assembled on the optical filter 160 opposite the lens tubes. Standoffs extending from the optical filter 160 can be similarly fabricated or installed around the diffuser(s) 180, and the image sensor can be aligned with and bonded to the standoffs opposite the optical filter 160. Other optical elements within the system (e.g., the bulk imaging lens, the bulk transmitting lens, etc.) can be fabricated according to similar techniques and with similar materials.

3. Two-Dimensional Optical System

[0056] Another variation of the system includes: a set of illumination sources 110 arranged in a first rectilinear grid array, each illumination source in the set of illumination sources 110 configured to output an illuminating beam of an operating wavelength toward a discrete spot in a field ahead of the illumination source; a bulk imaging optic 130 characterized by a focal plane opposite the field; an aperture layer coincident the focal plane, defining a set of apertures 144 in a second rectilinear grid array proportional to the first rectilinear grid array, and defining a stop region 146 around the set of apertures 144, each aperture in the set of apertures 144 defining a field of view in the field coincident a discrete spot output by a corresponding illumination source in the set of illumination sources 110, the stop region 146 absorbing light rays reflected from surfaces in the field outside of fields of view defined by the set of apertures 144 and passing through the bulk imaging optic 130; a set of lenses 150, each lens in the set of lenses 150 characterized by a second focal length, offset from the focal plane opposite the bulk imaging optic 130 by the

second focal length, aligned with an aperture in the set of apertures 144, and configured to collimate light rays passed by the aperture; an optical filter 160 adjacent the set of lenses 150 opposite the aperture layer and configured to pass light rays at the operating wavelength; a set of pixels 170 adjacent the optical filter 160 opposite the set of lenses 150, each pixel in the set of pixels 170 aligned with a subset of lenses in the set of lenses 150; and a diffuser 180 interposed between the optical filter 160 and the set of pixels 170 and configured to spread collimated light output from each lens in the set of lenses 150 across a corresponding pixel in the set of pixels 170.

[0057] Generally, in this variation, the system includes a two-dimensional grid array of channels (i.e., aperture, lens, and pixel sets or lens tube and pixel sets) and is configured to image a volume occupied by the system in two dimensions. The system can collect one-dimensional distance data – such as counts of incident photons within a sampling period and/or times between consecutive photons incident on pixels of known position corresponding to known fields of view in the field – across a two-dimensional field. The one-dimensional distance data can then be merged with known positions of the fields of view for each channel in the system to reconstruct a virtual three-dimensional representation of the field ahead of the system.

[0058] In this variation, the aperture layer can define a grid array of apertures, the set of lenses 150 can be arranged in a similar grid array with one lens aligned with one aperture in the aperture layer, and the set of pixels 170 can include one pixel per aperture and lens pair, as described above. For example, the aperture layer can define a 24-by-24 grid array of 200-µm-diameter apertures offset vertically and laterally by an aperture pitch distance of 300 µm, and the set of lenses 150 can similarly define a 24-by-24 grid array of lenses offset vertically and laterally by a lens pitch distance of 300 µm. In this example, the set of pixels 170 can include a 24-by-24 grid array of 300-µm-square pixels, wherein each pixel includes a 3x3 square array of nine 100-µm-square SPADs.

[0059] Alternatively, in this variation, the set of pixels 170 can include one pixel per group of multiple aperture and lens pairs. In the foregoing example, the set of pixels 170 can alternatively include a 12-by-12 grid array of 600-µm-square pixels, wherein each pixel includes a 6x6 square array of 36 100-µm-square SPADs and wherein each pixel is aligned with a group of four adjacent lenses in a square grid. In this example, for each group of four adjacent lenses, the diffuser 180: can bias collimated light rays output from a lens in the

(1,1) position in the square grid upward and to the right to spread light rays passing through the (1,1) lens across the full breadth and width of the corresponding pixel; can bias collimated light rays output from a lens in the (2,1) position in the square grid upward and to the left to spread light rays passing through the (2,1) lens across the full breadth and width of the corresponding pixel; can bias collimated light rays output from a lens in the (1,2) position in the square grid downward and to the right to spread light rays passing through the (1,2) lens across the full breadth and width of the corresponding pixel; and can bias collimated light rays output from a lens in the (2,2) position in the square grid downward and to the left to spread light rays passing through the (2,2) lens across the full breadth and width of the corresponding pixel, as shown in FIG. 8.

[0060] In the foregoing example, for each group of four illumination sources in a square grid and corresponding to one group of four lenses in a square grid, the system can actuate one illumination source in the group of four illumination sources at any given instance in time. In particular, for each group of four illumination sources in a square grid corresponding to one pixel in the set of pixels 170, the system can actuate a first illumination source 111 in a (1,1) position during a first sampling period to illuminate a field of view defined by a first aperture 141 corresponding to a lens in the (1,1) position in the corresponding group of four lenses, and the system can sample all 36 SPADs in the corresponding pixel during the first sampling period. The system can then shut down the first illumination source 111 and actuate a second illumination source 112 in a (1,2) position during a subsequent second sampling period to illuminate a field of view defined by a second aperture 142 corresponding to a lens in the (1,2) position in the corresponding group of four lenses, and the system can sample all 36 SPADs in the corresponding pixel during the second sampling period. Subsequently, the system can then shut down the first and second illumination sources 112 and actuate a third illumination source in a (2,1) position during a subsequent third sampling period to illuminate a field of view defined by a third aperture corresponding to a lens in the (2,1) position in the corresponding group of four lenses, and the system can sample all 36 SPADs in the corresponding pixel during the third sampling period. Finally, the system can shut down the first, second, and third illumination sources and actuate a fourth illumination source in a (2,2) position during a fourth sampling period to illuminate a field of view defined by a fourth aperture corresponding to a lens in the (2,2) position in the corresponding group of four lenses, and the system can sample all

36 SPADs in the corresponding pixel during the fourth sampling period. The system can repeat this process throughout its operation.

[0061] Therefore, in the foregoing example, the system can include a set of pixels 170 arranged across an image sensor 7.2 mm in width and 7.2 mm in length and can implement a scanning schema such that each channel in the system can access (can project light rays onto) a number of SPADs otherwise necessitating a substantially larger image sensor (e.g., a 14.4 mm by 14.4 mm image sensor). In particular, the system can implement a serial scanning schema per group of illumination sources to achieve an exponential increase in the dynamic range of each channel in the system. In particular, in this variation, the system can implement the foregoing imaging techniques to increase imaging resolution of the system.

[0062] In the foregoing implementation, the system can also include a shutter 182 between each channel and the image sensor, and the system can selectively open and close each shutter 182 when the illumination source for the corresponding channel is actuated and deactivated, respectively. For example, the system can include one independently-operable electrochromic shutter 182 interposed between each lens, and the system can open the electrochromic shutter 182 over the (1,1) lens in the square-gridded group of four lenses and close electrochromic shutters 182 over the (1,2), (2,1), and (2,2) lens when the (1,1) illumination source is activated, thereby rejecting noise passing through the (1,2), (2,1), and (2,2) lens from reaching the corresponding pixel on the image sensor. The system can therefore selectively open and close shutters 182 between each channel and the image sensor to increase SNR per channel during operation. Alternatively, the system can include one independently-operable electrochromic shutter 182 arranged over select regions of each pixel, as shown in FIG. 8, wherein each electrochromic shutter 182 is aligned with a single channel (i.e., with a single lens in the set of lenses). The system can alternatively include MEMS mechanical shutters or any other suitable type of shutter interposed between the set of lenses 150 and the image sensor.

[0063] In this variation, the system can define two-dimension grid arrays of apertures, lenses, diffusers, and/or pixels characterized by a first pitch distance along a first (e.g., X) axis and a second pitch distance – different from the first pitch distance – along a second (e.g., Y) axis. For example, the image sensor can include pixels offset by a 25μm horizontal pitch and a 300μm vertical pitch, wherein each pixel includes a single row of twelve subpixels.

[0064] However, in this variation, the two-dimensional optical system can include an array of any other number and pattern of channels (e.g., apertures, lenses (or lens tubes), and diffusers) and pixels and can execute any other suitable scanning schema to achieve higher spatial resolutions per channel than the raw pixel resolution of the image sensor. The system can additionally or alternatively include a converging optic, a diverging optic, and/or any other suitable type of optical element to spread light rights passed from a channel across the breadth of a corresponding pixel.

[0065] As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the embodiments of the invention without departing from the scope of this invention as defined in the following claims.

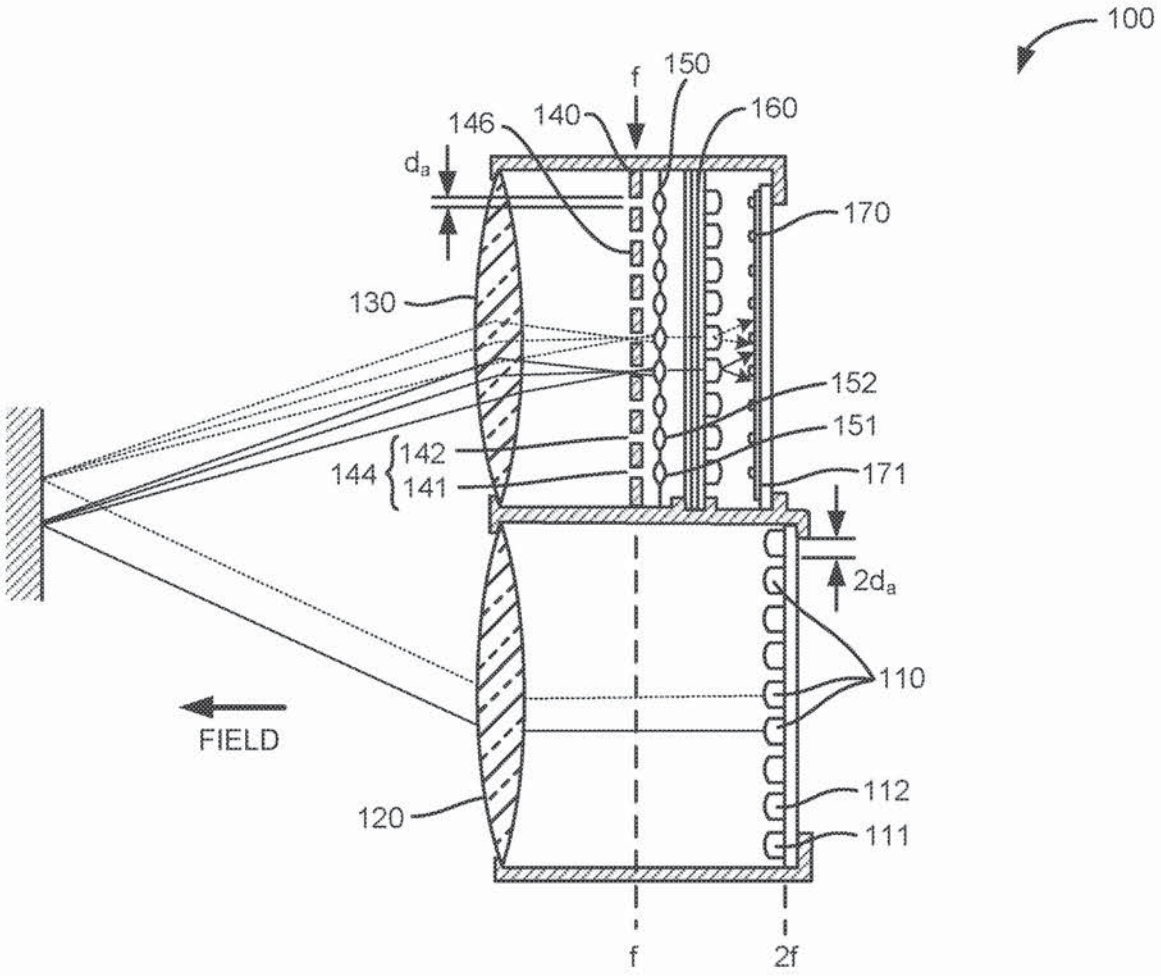

100
f
150
146
140
160
d_a
170
130
152
151
142
144
141
171
$2d_a$
110
FIELD
120
112
111
f
2f

FIG. 1

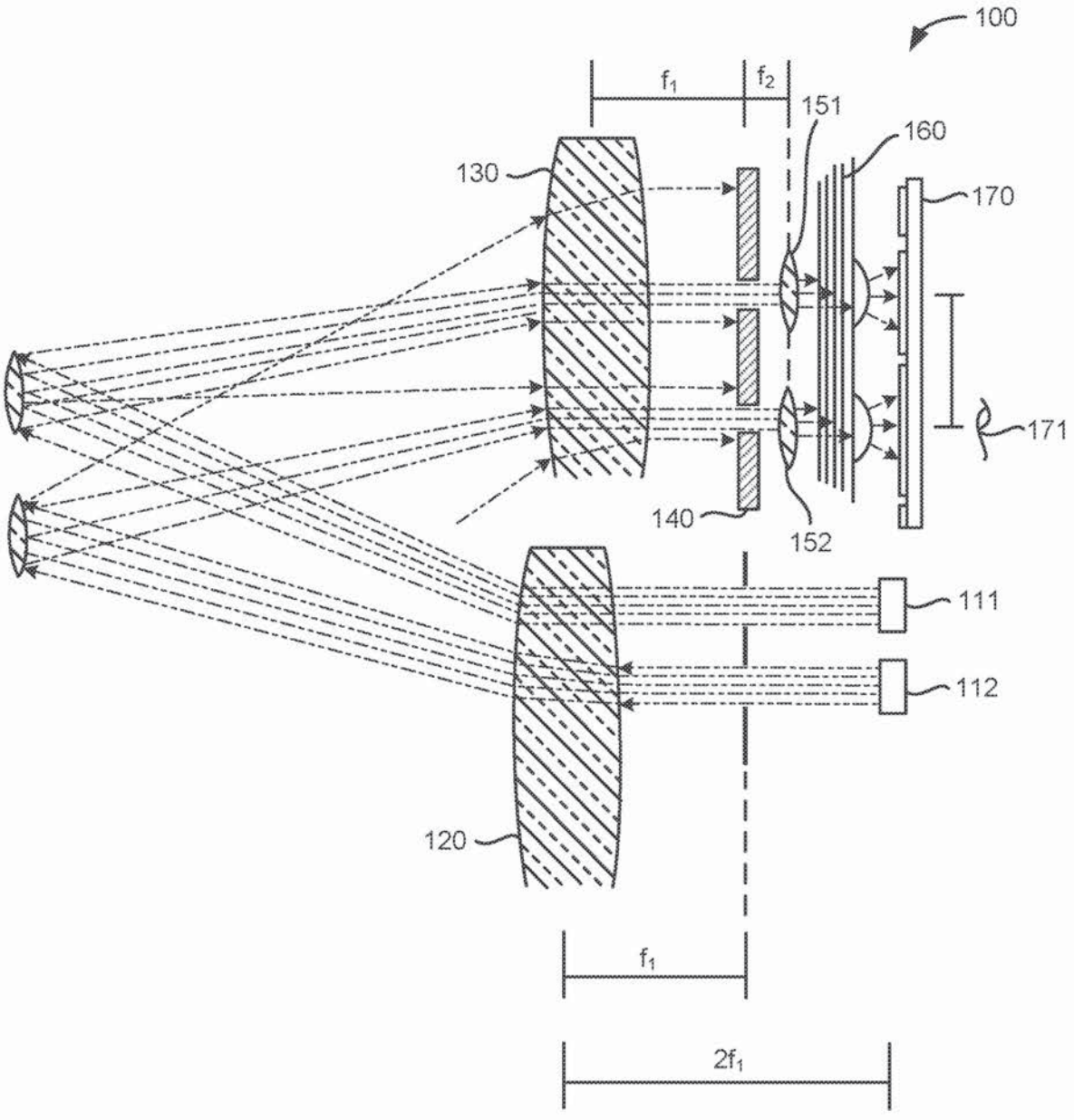


FIG. 2

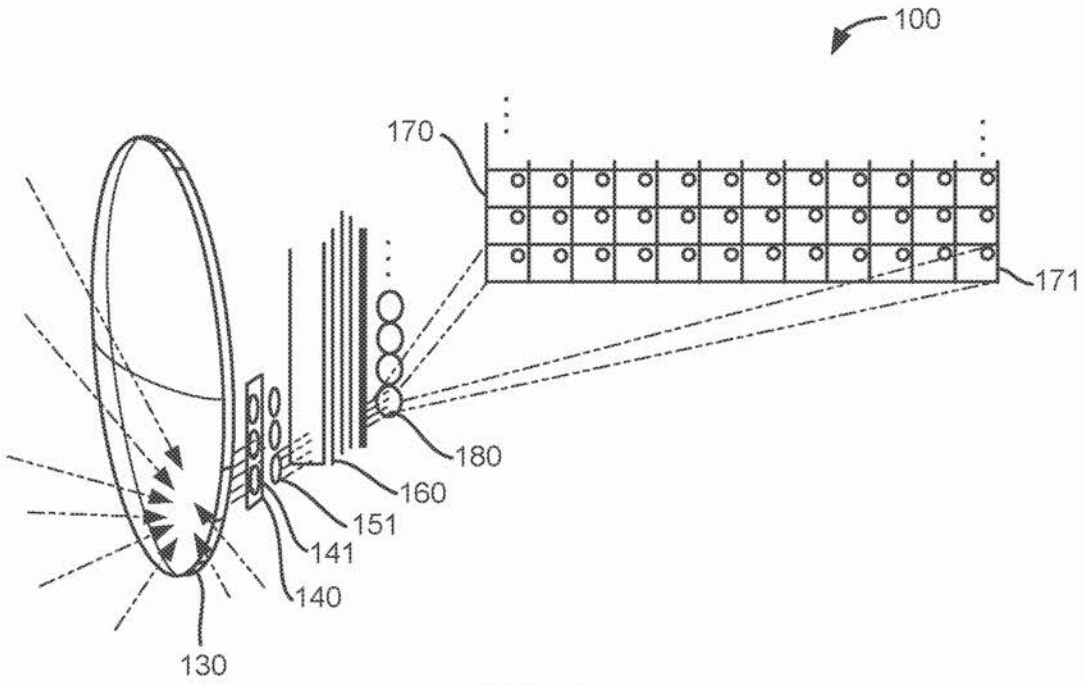


FIG. 3

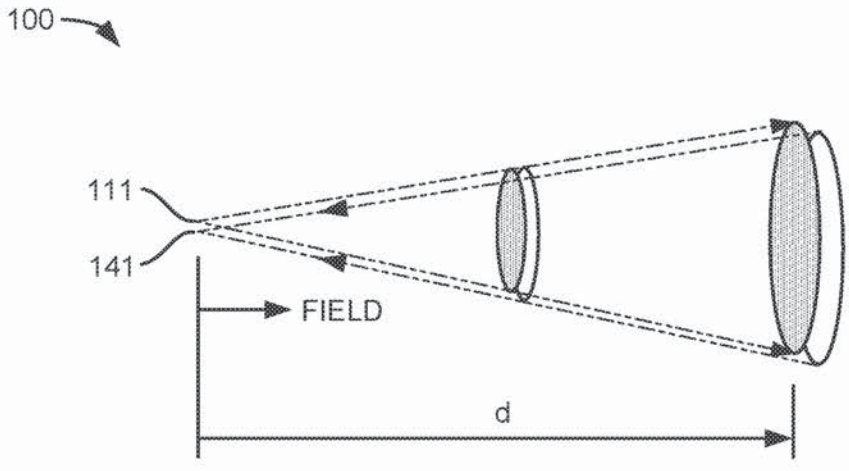


FIG. 4

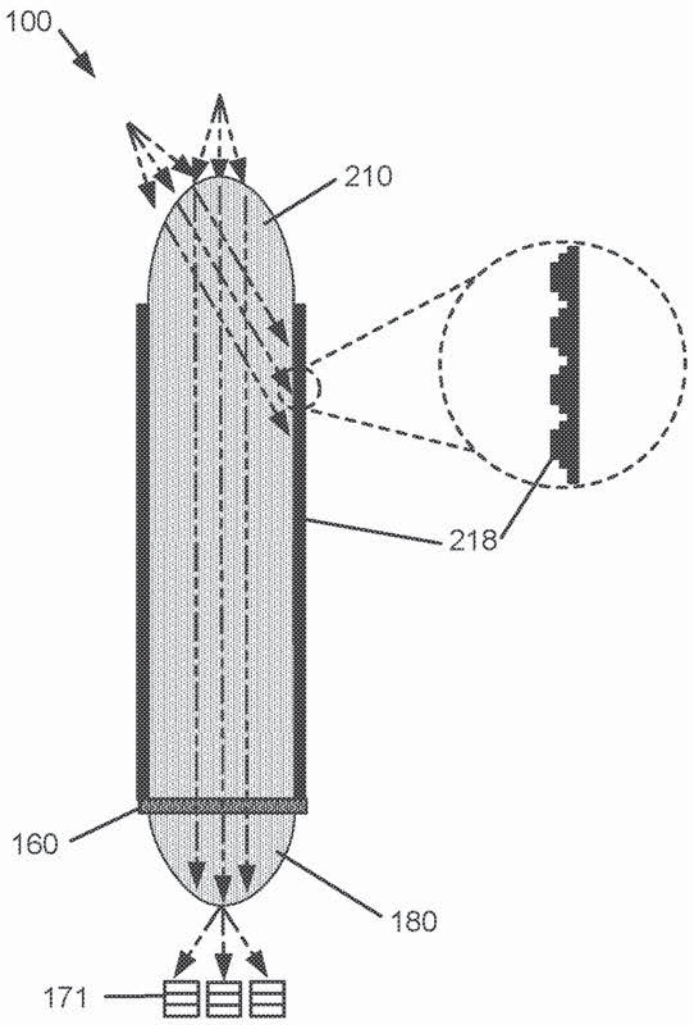


FIG. 5

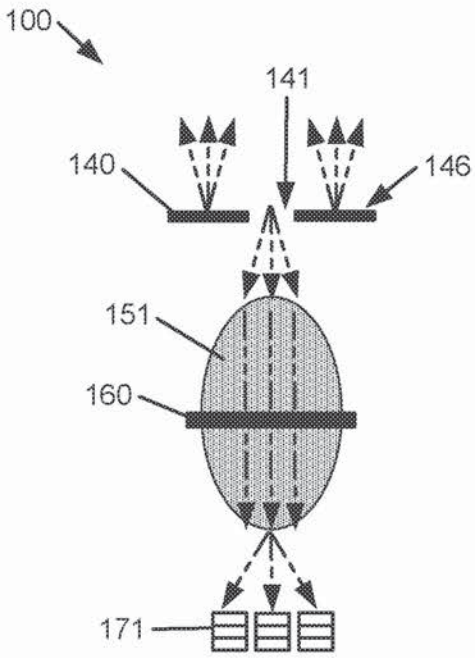


FIG. 6

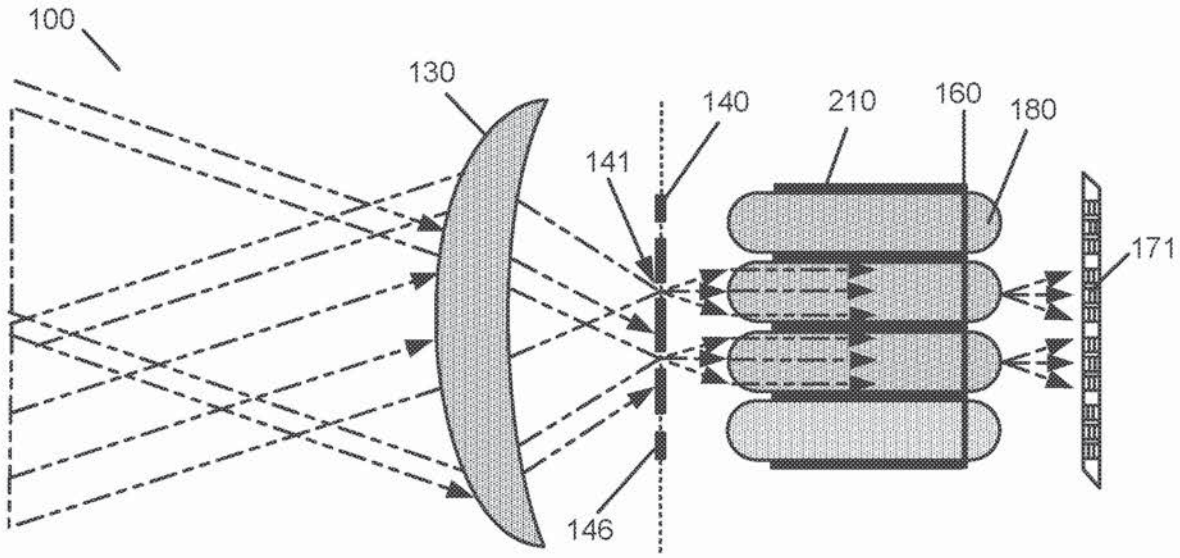

100
130
140
210
160
180
141
171
146

FIG. 7

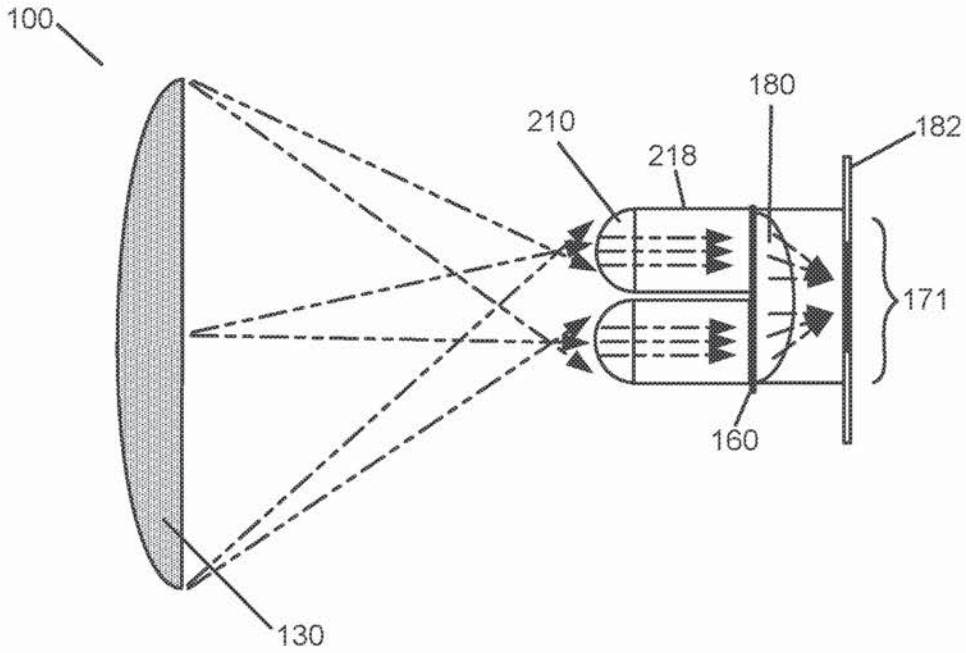

100
180
210
182
218
171
160
130

FIG. 8

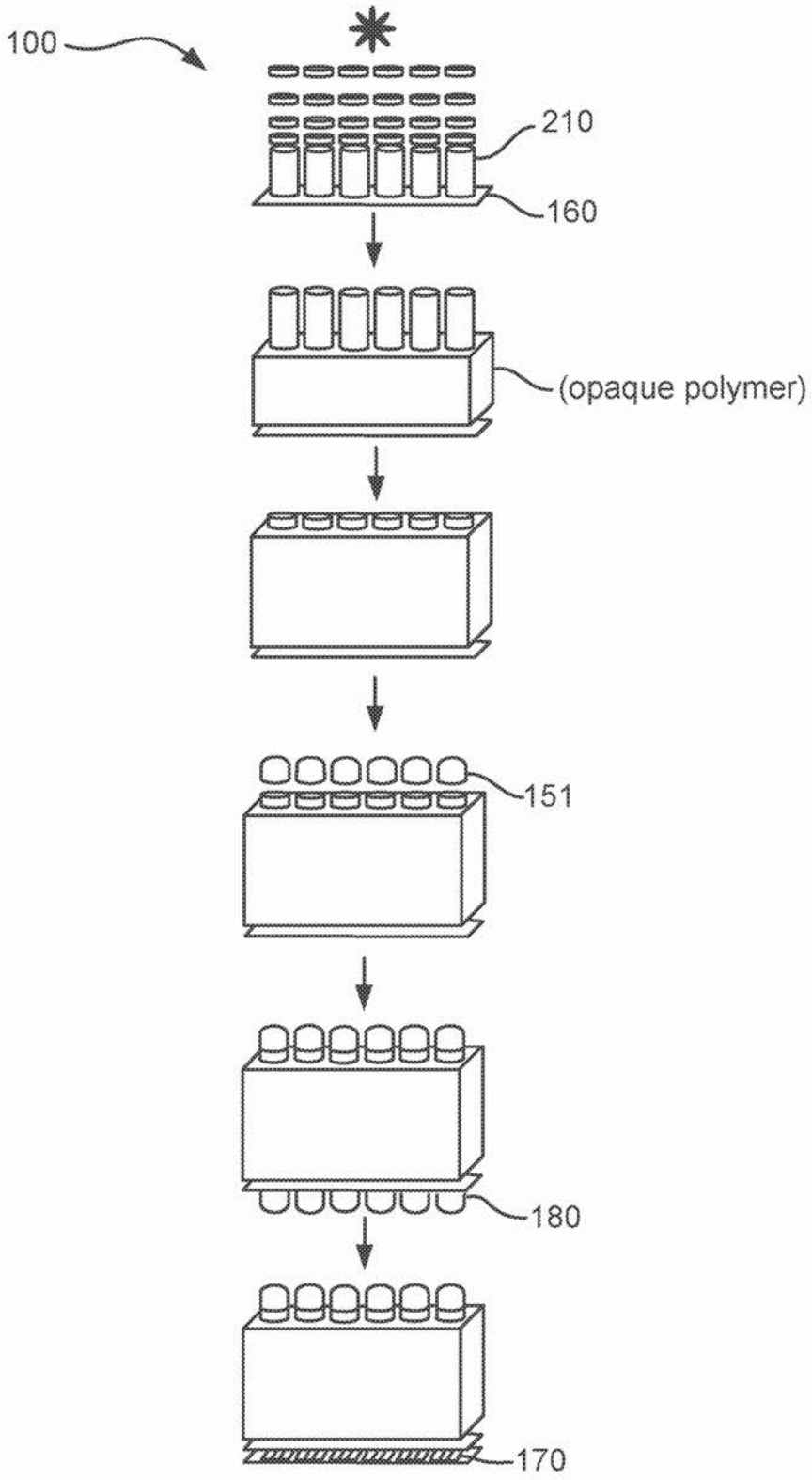


FIG. 9

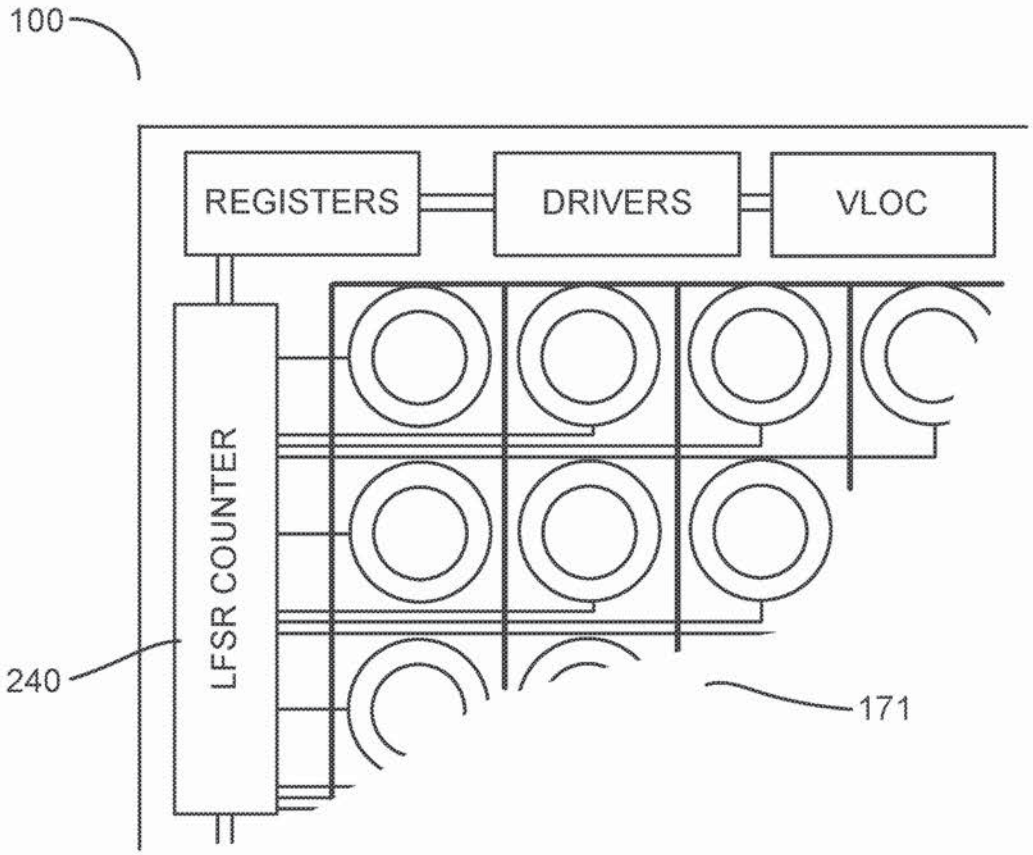


FIG. 10

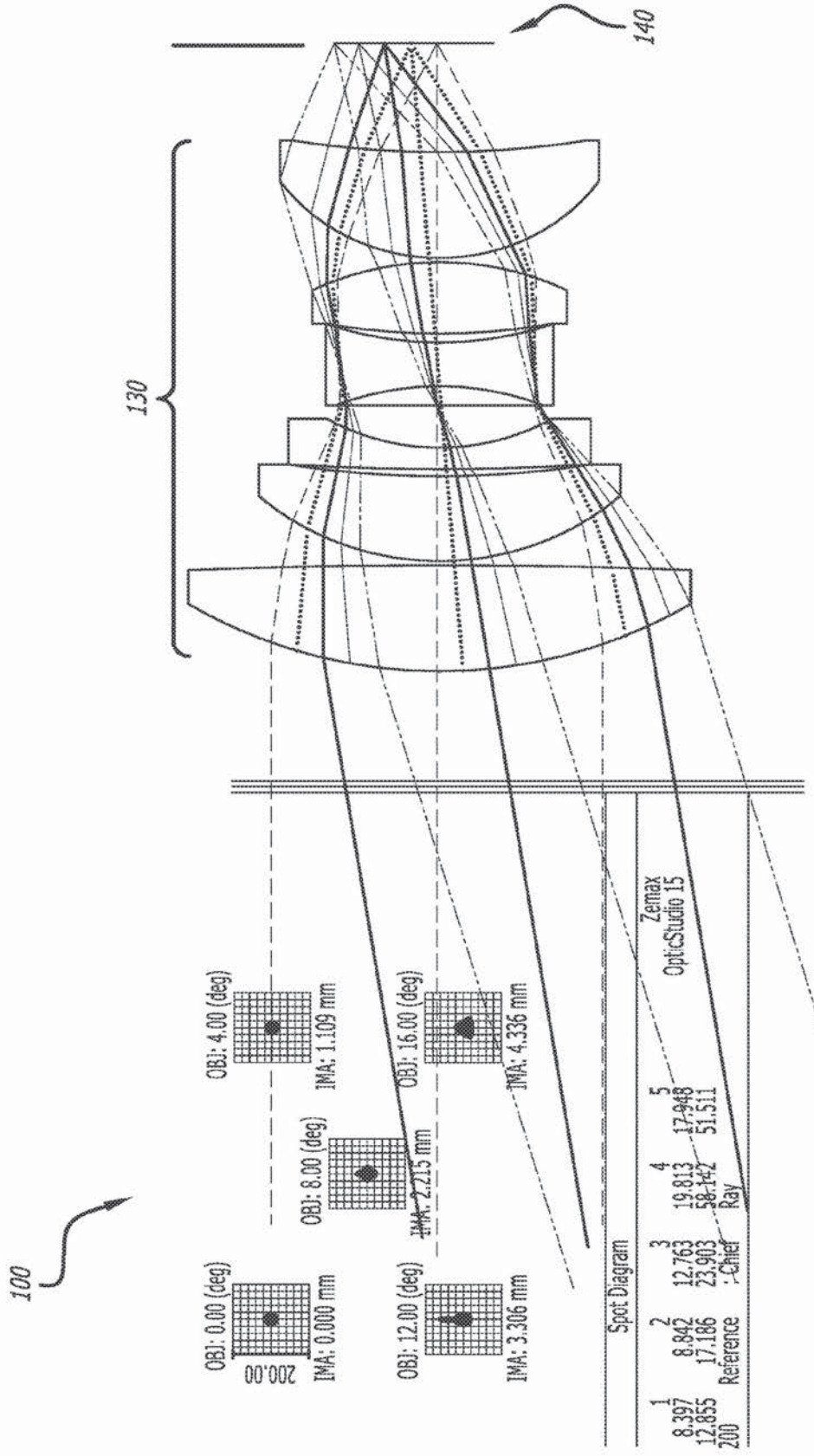

100
130
140
OBJ: 0.00 (deg)
IMA: 0.000 mm
OBJ: 4.00 (deg)
IMA: 1.109 mm
OBJ: 8.00 (deg)
IMA: 2.215 mm
OBJ: 12.00 (deg)
IMA: 3.306 mm
OBJ: 16.00 (deg)
IMA: 4.336 mm
Zemax
OpticStudio 15
Spot Diagram
Ray
Chief
Reference

FIG. 11

I hereby certify that this correspondence is being filed via EFS-Web with the United States Patent and Trademark Office on July 25, 2018.

KILPATRICK TOWNSEND & STOCKTON LLP

By: /La Renda Meyer/

PATENT
Attorney Docket No.: 103033-P001USC2-1096583
Client Ref. No.: P001USC2

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	Confirmation No.: Herewith
Angus PACALA, *et al.*	Examiner: Not yet assigned
Application No.: Herewith	Technology Center/Art Unit: Not yet assigned
Filed: July 16, 2018	
For: OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS	INFORMATION DISCLOSURE STATEMENT
Customer No.: 20350	

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

The references cited on attached form PTO/SB/08A are being called to the attention of the Examiner. In accordance with the provisions of 37 CFR §1.98(a)(2), copies of any cited U.S. Patent and U.S. Patent Application Publications are not provided. Copies of the remaining cited references are provided.

The following applications are related to this application: 15/880,491, filed January 25, 2018, 15/276,532, filed September 26, 2016 and 15/861,330. Copies of any Office Actions in such Patent Applications are available via the USPTO's PAIR or electronic file wrapper system and are believed to be readily accessible to the Examiner. Thus, although Applicant may submit copies of some such Office Actions, Applicant does not represent that copies of all, or the most significant, Office Actions are being

supplied. If the Examiner desires copies of all such Office Actions, the Examiner should contact the undersigned.

It is respectfully requested that the cited references be expressly considered during the prosecution of this application, and the references be made of record therein and appear among the "references cited" on any patent to issue therefrom.

As provided for by 37 CFR §1.97(g) and (h), no inference should be made that the information and references cited are prior art merely because they are in this statement and no representation is being made that a search has been conducted or that this statement encompasses all the possible relevant information.

This IDS is being filed before the mailing date of the first Office Action on the merits. Applicant believes that no fee is required for submission of this statement. However, if any additional fees are due for the submission of this Information Disclosure Statement, please deduct those fees from Deposit Account No. 20-1430.

Respectfully submitted,

/ William L. Shaffer /

William L. Shaffer
Registration No. 37,234

KILPATRICK TOWNSEND & STOCKTON LLP

Document code: WFEE

United States Patent and Trademark Office
Sales Receipt for Accounting Date: 09/05/2018

MNGUYEN	SALE	#00000013	Mailroom Dt:	07/26/2018		201430	16046643
		01	FC : 2202	400.00	DA		
		02	FC : 2201	230.00	DA		

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	Confirmation No.: 1720
Angus Pacala, et al.	Examiner: Not yet assigned
Application No.: 16/046,643	Art Unit: Not yet assigned
Filed: July 26, 2018	
For: OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS	**PRELIMINARY AMENDMENT**
Customer No.: 20350	

Mail Stop: Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

Prior to examination of the above-referenced application, please enter the following amendments and remarks:

Amendments to the Claims are reflected in the listing of claims which begins on page 2 of this paper.

Remarks/Arguments begin on page 9 of this paper.

Amendments to the Claims

This listing of claims will replace all prior versions, and listings of claims in the application.

Listing of Claims:

1. (Currently Amended) An optical imaging system comprising:

a bulk receiver optic having a focal plane;

an array of pixels; and

an aperture layer disposed between the bulk receiver optic and the array of pixels, the aperture layer including a plurality of discrete apertures coincident with the focal plane, wherein the aperture layer and pixel layer are arranged to form a plurality of sense channels defining a plurality of discrete, non-overlapping fields of view beyond a threshold distance in a field external to the optical imaging system, each sense channel in the plurality of sense channels including a pixel from the array of pixels and an aperture from the plurality of apertures that defines the field of view for its respective pixel, and wherein a sensing pixel area of each pixel in the plurality of sense channels is larger than an area of its corresponding aperture in the plurality of apertures.

2. (Currently Amended) The optical imaging system of claim 1 wherein each pixel in the array of pixels comprises a plurality of subpixels distributed across its sensing pixel area.

3. (Original) The optical imaging system of claim 2 wherein the plurality of subpixels in each pixel is a plurality of SPADs.

4. (Original) The optical imaging system of claim 1 further comprising, within each channel in the plurality of sense channels, an optical filter disposed between the bulk receiving optic and the array of pixels, the optical filter configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation while blocking radiation outside the band.

5. (Original) The optical imaging system of claim 1 further comprising:

a bulk transmitter optic; and

an illumination source comprising a plurality of lasers corresponding in number to the plurality of sense channels, each laser in the plurality of lasers configured to project a discrete illuminating beam at an operating wavelength through the bulk transmitter optic into a field of view that is substantially the same size and geometry as a field of view defined by the bulk receiver optic and a corresponding aperture in the plurality of sense channels.

6. (Original) The optical imaging system of claim 5 wherein each laser in the plurality of lasers is a VCSEL.

7. (Original) The optical imaging system of claim 5 wherein a diameter of each discrete beam projected from the illumination source is substantially similar to a cross-section of the field of view of its respective channel at various distances from the bulk imaging optic.

8. (Original) The optical imaging system of claim 5 further comprising, within each channel in the plurality of sense channels, an optical filter disposed between the bulk receiving optic and the array of pixels, the optical filter configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation that includes the operating wavelength of the plurality of lasers to the plurality of pixels while blocking radiation outside the band.

9. (Original) The optical imaging system of claim 8 further comprising, within each channel in the plurality of sense channels, a diffuser disposed within the channel between the aperture and the pixel.

10. (Original) The optical imaging system of claim 5 wherein each laser in the plurality of lasers is a VCSEL, each pixel in the array of pixels comprises a plurality of SPADs and an optical filter is disposed between the bulk receiving optic and the array of pixels, the optical filter configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation that includes the operating wavelength of the plurality of VCSELs to the array of pixels while blocking radiation outside the band.

11. (Original) The optical imaging system of claim 1 further comprising a plurality of lenses, wherein each channel in the plurality of channels includes a lens from the plurality of lenses disposed between the aperture of the channel and its corresponding pixel.

12. (Original) The optical imaging system of claim 1 wherein adjacent apertures in the aperture layer are offset by an aperture pitch distance greater than a diameter of each aperture.

13. (Currently Amended) An optical imaging system comprising:

a bulk receiver optic having a focal plane;

an array of pixels of substantially uniform sensing pixel area, each pixel in the array of pixels including a plurality of subpixels distributed across its sensing pixel area; and

an aperture layer disposed between the bulk receiver optic and the array of pixels, the aperture layer including a plurality of discrete apertures of substantially uniform area formed coincident with the focal plane and stop regions interposed between adjacent apertures in the aperture layer, wherein the aperture layer and pixel layer are arranged to form a plurality of sense channels defining a plurality of discrete, non-overlapping fields of view beyond a threshold distance in a field external to the optical imaging system, each sense channel in the plurality of sense channels including an aperture from the plurality of apertures and a pixel from the array of pixels with the aperture of each channel defining the field of view for its respective pixel, and wherein the area of the aperture in each channel is smaller than the sensing pixel area of its respective pixel.

14. (Original) The optical imaging system of claim 13 wherein the plurality of subpixels in each pixel is a plurality of SPADs.

15. (Original) The optical imaging system of claim 13 further comprising:

a bulk transmitter optic; and

an illumination source comprising a plurality of lasers corresponding in number to the plurality of sense channels, each laser in the plurality of lasers configured to project a discrete illuminating beam at an operating wavelength through the bulk transmitter optic into a

field of view that is substantially the same size and geometry as a field of view defined by the bulk receiver optic and a corresponding aperture in the plurality of sense channels.

16. (Original) The optical imaging system of claim 15 wherein each aperture in the plurality of discrete apertures defines a field of view in the field coincident a discrete spot output by a corresponding laser in the plurality of lasers.

17. (Currently Amended) An optical imaging system comprising:

a bulk receiver optic having a focal plane;

an optical assembly having a plurality of sense channels defining a plurality of discrete, non-overlapping fields of view beyond a threshold distance in a field external to the bulk receiver optic, the optical assembly comprising:

an array of pixels of substantially uniform sensing pixel area, each pixel in the array of pixels including a plurality of subpixels distributed across its sensing pixel area;

an aperture layer disposed between the bulk receiver optic and the array of pixels, the aperture layer including a plurality of discrete apertures of substantially uniform area formed coincident with the focal plane and stop regions between adjacent apertures;

a lens layer including a plurality of lenses arranged to receive light passed through the aperture and pass the received light towards the array of pixels; and

an optical filter layer disposed between the bulk receiving optic and the array of pixels, the optical filter layer configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation while blocking radiation outside that band;

wherein each sense channel in the optical assembly includes a pixel from the array of pixels, an aperture from the aperture layer that defines the field of view for its respective pixel and has an area that is smaller than a sensing area of its respective pixel, a lens from the lens layer and a filter from the optical filter layer.

18. (Original) The optical imaging system of claim 17 wherein adjacent apertures in the aperture layer are offset by an aperture pitch distance greater than a diameter of each aperture and substantially equal to a pitch between adjacent lenses in the lens layer.

19. (Original) The optical imaging system of claim 18 wherein the optical filter layer is disposed between the lens layer and the array of pixels and wherein each lens is configured to collimate light rays passed by its respective aperture so that light rays incident on the optical filter meet the optical filter at an angle of incidence of approximately 0 degrees.

20. (Original) The optical imaging system of claim 18 further comprising:

a bulk transmitter optic; and

an illumination source comprising a plurality of lasers corresponding in number to the plurality of sense channels, each laser in the plurality of lasers configured to project a discrete illuminating beam at an operating wavelength through the bulk transmitter optic into a field of view that is substantially the same size and geometry as a field of view defined by the bulk receiver optic and a corresponding aperture in the plurality of sense channels.

21. (Original) The optical imaging system of claim 20 wherein the plurality of subpixels in each pixel is a plurality of SPADs and where the plurality of lasers in the illumination source is a plurality of VCSELs.

22. (Original) The optical imaging system of claim 21 wherein each aperture has a diameter of 200 microns or less.

23. (Original) The optical imaging system of claim 21 wherein each aperture has a diameter approaching the diffraction-limited diameter for the wavelength of light output by the plurality of lasers.

24. (Original) The optical imaging system of claim 21 wherein each aperture has a diameter less than the diffraction-limited diameter for the wavelength of light output by the plurality of lasers.

25. (Original) The optical imaging system of claim 21 wherein each aperture has a diameter matched to a dynamic range of its corresponding pixel.

26. (Original) The optical imaging system of claim 21 wherein the stop region surrounding each aperture blocks light rays reflected from a region of the surface outside the field of view of its corresponding aperture.

Per Angus, draft claim where the "pixel pitch is greater than the aperture diameter in the case of circular apertures, or the maximum linear dimension in the case of non-circular apertures"

27. (New) An optical imaging system comprising:

a bulk receiver optic having a focal plane;

a plurality of pixels arranged in a pixel array in which adjacent pixels in the array are spaced apart from each other in a first dimension by a pixel pitch; and

an aperture layer disposed between the bulk receiver optic and the plurality of pixels arranged in the pixel array, the aperture layer including a plurality of discrete apertures of substantially uniform size coincident with the focal plane and stop regions between adjacent apertures, wherein the plurality of discrete apertures are arranged in an aperture array in which adjacent apertures in the aperture array are spaced apart from each other in the first dimension by an aperture pitch and wherein the aperture array is aligned with the pixel array and a maximum linear dimension of each aperture in the aperture array is less than the pixel pitch; and

wherein the aperture layer and pixel layer are arranged to form a plurality of sense channels defining a plurality of discrete, non-overlapping fields of view beyond a threshold distance in a field external to the optical imaging system, each sense channel in the plurality of sense channels including a pixel from the array of pixels and an aperture from the plurality of apertures that defines the field of view for its respective pixel.

28. (New) The optical imaging system of claim 27 wherein each aperture in the plurality of discrete apertures is a circular aperture of substantially uniform diameter.

29. (New) The optical imaging system of claim 27 wherein the aperture pitch is substantially equal to the pixel pitch.

30. (New) The optical imaging system of claim 27 wherein each pixel in the plurality of pixels comprises a plurality of subpixels distributed across a pixel area.

31. (New) The optical imaging system of claim 29 wherein the plurality of subpixels in each pixel is a plurality of SPADs.

32. (New) The optical imaging system of claim 27 further comprising, within each channel in the plurality of sense channels, an optical filter disposed between the bulk receiving optic and the pixel within the channel, the optical filter configured to receive light passed through the bulk receiving optic and pass a narrow band of radiation while blocking radiation outside the band.

33. (New) The optical imaging system of claim 32 further comprising:

a bulk transmitter optic; and

an illumination source comprising a plurality of lasers corresponding in number to the plurality of sense channels, each laser in the plurality of lasers configured to project a discrete illuminating beam at an operating wavelength through the bulk transmitter optic into a field of view that is substantially the same size and geometry as a field of view defined by the bulk receiver optic and a corresponding aperture in the plurality of sense channels; and

wherein the narrow band of radiation passed by the optical filter includes the operating wavelength.

34. (New) The optical imaging system of claim 33 wherein each laser in the plurality of lasers is a VCSEL.

REMARKS/ARGUMENTS

Upon entry of the present amendment, claims 1-34 will be pending in this application. Claims 1, 2, 13, and 17 have been amended, and new claims 27-34 have been added.

Applicants respectfully assert that the claims are all supported by the application as originally filed and that no new matter is added.

CONCLUSION

In view of the foregoing, Applicant believes all claims now pending in this Application are in condition for examination.

Except for the issue fees payable under 37 C.F.R. § 1.18, the Director is authorized to charge any additional fees during pendency of this application, including any required extension of time fees, or credit any overpayment to Deposit Account Number 20-1430. This paragraph is intended to be a constructive petition for extension of time in accordance with 37 C.F.R. § 1.136(a)(3).

If the Examiner believes a telephone conference would expedite prosecution of this application, please contact the undersigned at 858-350-6104 or WShaffer@kilpatricktownsend.com.

Respectfully submitted,

/ William L. Shaffer /

William L. Shaffer
Registration No. 37,234

KILPATRICK TOWNSEND & STOCKTON LLP

Electronic Acknowledgement Receipt	
EFS ID:	33416411
Application Number:	16046643
International Application Number:	
Confirmation Number:	1720
Title of Invention:	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
First Named Inventor/Applicant Name:	Angus Pacala
Customer Number:	20350
Filer:	William Leland Shaffer/La Renda Meyer
Filer Authorized By:	William Leland Shaffer
Attorney Docket Number:	103033-P001USC2-1096583
Receipt Date:	08-AUG-2018
Filing Date:	
Time Stamp:	19:51:50
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1		PreliminaryAmendment_P001 USC2-1096583.pdf	114333 55ab69717ae75ec6db197a46a52b9da0879 1f45a	yes	9

	Multipart Description/PDF files in .zip description		
	Document Description	**Start**	**End**
	Preliminary Amendment	1	1
	Claims	2	8
	Applicant Arguments/Remarks Made in an Amendment	9	9
Warnings:			
Information:			
	Total Files Size (in bytes):	114333	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.
National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.
New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

PTO/SB/06 (09-11)
Approved for use through 1/31/2014. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

PATENT APPLICATION FEE DETERMINATION RECORD Substitute for Form PTO-875	Application or Docket Number 16/046,643	Filing Date 07/26/2018	☐ To be Mailed

ENTITY: ☐ LARGE ☑ SMALL ☐ MICRO

APPLICATION AS FILED - PART I

FOR	(Column 1) NUMBER FILED	(Column 2) NUMBER EXTRA		RATE ($)	FEE ($)
☐ BASIC FEE (37 CFR 1.16(a), (b), or (c))	N/A	N/A		N/A	
☐ SEARCH FEE (37 CFR 1.16(k), (i), or (m))	N/A	N/A		N/A	
☐ EXAMINATION FEE (37 CFR 1.16(o), (p), or (q))	N/A	N/A		N/A	
TOTAL CLAIMS (37 CFR 1.16(i))	minus 20 =	*		x $50 =	
INDEPENDENT CLAIMS (37 CFR 1.16(h))	minus 3 =	*		x $230 =	
☐ APPLICATION SIZE FEE (37 CFR 1.16(s))	If the specification and drawings exceed 100 sheets of paper, the application size fee due is $310 ($155 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s).				
☐ MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j))					
* If the difference in column 1 is less than zero, enter "0" in column 2.				TOTAL	

APPLICATION AS AMENDED - PART II

		(Column 1)		(Column 2)	(Column 3)			
AMENDMENT	08/08/2018	CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA		RATE ($)	ADDITIONAL FEE ($)
	Total (37 CFR 1.16(i))	* 34	Minus	** 34	= 0		x $50 =	0
	Independent (37 CFR 1.16(h))	* 4	Minus	*** 4	= 0		x $230 =	0
	☐ Application Size Fee (37 CFR 1.16(s))							
	☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))							
							TOTAL ADD'L FEE	0

		(Column 1)		(Column 2)	(Column 3)			
AMENDMENT		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA		RATE ($)	ADDITIONAL FEE ($)
	Total (37 CFR 1.16(i))	*	Minus	**	=		x $0 =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=		x $0 =	
	☐ Application Size Fee (37 CFR 1.16(s))							
	☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))							
							TOTAL ADD'L FEE	

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.	LDRC
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20".	/eva gillis/
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3".	
The "Highest Number Previously Paid For" (Total or Independent) is the highest number found in the appropriate box in column 1.	

This collection of information is required by 37 CFR 1.16. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

DECLARATION FOR UTILITY OR DESIGN PATENT APPLICATION (37 CFR 1.63)

☐ Declaration Submitted with Initial Filing OR ☒ Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16(f)) required)

Attorney Docket Number	10176P001
First Named Inventor	Angus Pacala
COMPLETE IF KNOWN	
Application Number	15/276,532
Filing Date	September 26, 2016
Art Unit	
Examiner Name	

Optical System for Collecting Distance Information Within a Field

(Title of the Invention)

As a below named inventor, I hereby declare that:

This declaration is directed to:

☐ The attached application,

OR

☒ United States Application Number or PCT International Application Number **15/276,532**

filed on **09/26/2016**

The above-identified application was made or authorized to be made by me.

I believe I am the original inventor or an original joint inventor of a claimed invention in the application.

I have reviewed and understand the contents of the above-identified application, including the claim(s).

I am aware of the duty to disclose to the Patent and Trademark Office all information known to me to be material to patentability as defined in 37 CFR 1.56, including for a continuation-in-part application, information material to patentability that became available between the filing date of the prior application and the national or PCT international filing date of the continuation-in-part application.

I hereby acknowledge that any willful false statement made in this declaration is punishable under 18 U.S.C. 1001 by fine or imprisonment of not more than five (5) years, or both.

Willful false statements and the like are punishable by fine or imprisonment, or both (18 U.S.C. 1001), and may jeopardize the validity of the application or any patent issuing thereon. I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true.

Authorization To Permit Access to Application by Participating Offices

☒

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the above-identified patent application is filed access to the above-identified patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the above-identified patent application is filed to have access to the above-identified patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the above-identified patent application with respect to: 1) the above-identified patent application-as-filed; 2) any foreign application to which the above-identified patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the above-identified patent application; and 3) any U.S. application-as-filed from which benefit is sought in the above-identified patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date of filing the Authorization to Permit Access to Application by Participating Offices.

Based on Forms PTO/AIA/08 and PTO/AIA/10 (06-12) as modified by Blakely, Sokoloff, Taylor & Zafman LLP on 09/17/2012.

DECLARATION -- Utility or Design Patent Application

Direct all correspondence to: ☒	The address associated with Customer Number:	08791	OR ☐	Correspondence address below:

Name		
Address	BLAKELY SOKOLOFF TAYLOR & ZAFMAN LLP 1279 Oakmead Parkway	
City Sunnyvale	State California	Zip 94085-4040
Country U.S.A.	Telephone (408) 720-8300	Email MAIL@BSTZ.com

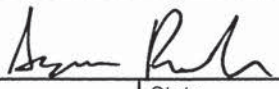
WARNING:

Petitioner/applicant is cautioned to avoid submitting personal information in documents filed in a patent application that may contribute to identity theft. Personal information such as social security numbers, bank account numbers, or credit card numbers (other than a check or credit card authorization form PTO-2038 submitted for payment purposes) is never required by the USPTO to support a petition or an application. If this type of personal information is included in documents submitted to the USPTO, petitioners/applicants should consider redacting such personal information from the documents before submitting them to the USPTO. Petitioner/applicant is advised that the record of a patent application is available to the public after publication of the application (unless a non-publication request in compliance with 37 CFR 1.213(a) is made in the application) or issuance of a patent. Furthermore, the record from an abandoned application may also be available to the public if the application is referenced in a published application or an issued patent (see 37 CFR 1.14). Checks and credit card authorization forms PTO-2038 submitted for payment purposes are not retained in the application file and therefore are not publicly available. Petitioner/applicant is advised that documents which form the record of a patent application (such as the PTO/SB/01) are placed into the Privacy Act system of records DEPARTMENT OF COMMERCE, COMMERCE-PAT-7, System name: *Patent Application File* . Documents not retained in an application file (such as the PTO-2038) are placed into the Privacy Act system of COMMERCE/PAT-TM-10, System name: *Deposit Accounts and Electronic Funds Transfer Profiles.*

Legal Name of Sole or First Inventor:

(*E.g.*, Given Name (first and middle (if any)) and Family Name or Surname)

Angus Pacala

Inventor's Signature 		Date 11/25/2016
Residence: City San Francisco	State CA	Country US
Mailing Address 268 Clara St.		
City San Francisco	State CA	Zip 94107	Country US

10176P001

Based on Forms PTO/AIA/08 and PTO/AIA/10 (06-12) as modified by Blakely, Sokoloff, Taylor & Zafman LLP on 09/17/2012.

DECLARATION -- Utility or Design Patent Application

Legal Name of Additional Joint Inventor, if any:

(*E.g.*, Given Name (first and middle (if any)) and Family Name or Surname)

Mark Frichtl

Inventor's Signature	Date
Mark Frichtl	**11/25/2016**

Residence: City	State	Country
San Francisco	CA	US

Mailing Address

268 Clara St.

City	State	Zip	Country
San Francisco	CA	94107	US

Legal Name of Additional Joint Inventor, if any:

(*E.g.*, Given Name (first and middle (if any)) and Family Name or Surname)

Inventor's Signature	Date

Residence: City	State	Country

Mailing Address

City	State	Zip	Country

Legal Name of Additional Joint Inventor, if any:

(*E.g.*, Given Name (first and middle (if any)) and Family Name or Surname)

Inventor's Signature	Date

Residence: City	State	Country

Mailing Address

City	State	Zip	Country

Based on Forms PTO/AIA/08 and PTO/AIA/10 (06-12) as modified by Blakely, Sokoloff, Taylor & Zafman LLP on 09/17/2012.

Electronic Patent Application Fee Transmittal

Application Number:	16046643
Filing Date:	
Title of Invention:	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
First Named Inventor/Applicant Name:	Angus Pacala
Filer:	William Leland Shaffer/La Renda Meyer
Attorney Docket Number:	103033-P001USC2-1096583

Filed as Small Entity

Filing Fees for Utility under 35 USC 111(a)

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
Miscellaneous-Filing:				
LATE FILING FEE FOR OATH OR DECLARATION	2051	1	80	80
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Extension-of-Time:				
Miscellaneous:				
			Total in USD ($)	**80**

Electronic Acknowledgement Receipt	
EFS ID:	33508857
Application Number:	16046643
International Application Number:	
Confirmation Number:	1720
Title of Invention:	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
First Named Inventor/Applicant Name:	Angus Pacala
Customer Number:	20350
Filer:	William Leland Shaffer/La Renda Meyer
Filer Authorized By:	William Leland Shaffer
Attorney Docket Number:	103033-P001USC2-1096583
Receipt Date:	22-AUG-2018
Filing Date:	
Time Stamp:	16:39:40
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	CARD
Payment was successfully received in RAM	$80
RAM confirmation Number	082318INTEFSW16411100
Deposit Account	201430
Authorized User	IP eFiling
The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows: 37 CFR 1.16 (National application filing, search, and examination fees) 37 CFR 1.17 (Patent application and reexamination processing fees)	

37 CFR 1.19 (Document supply fees)

37 CFR 1.20 (Post Issuance fees)

37 CFR 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Oath or Declaration filed	signed_decs_P001USC2.pdf	209496 7850285f96bd8427c4273596e73a2d26dc83c17e	no	3
Warnings:					
Information:					
2	Fee Worksheet (SB06)	fee-info.pdf	30385 c029ef80cf5feffefb6afb6fcaeb666506d40d89	no	2
Warnings:					
Information:					
		Total Files Size (in bytes):	239881		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY.DOCKET.NO	TOT CLAIMS	IND CLAIMS
16/046,643	07/26/2018	2414	1795	103033-P001USC2-1096583	34	4

CONFIRMATION NO. 1720

FILING RECEIPT

20350
KILPATRICK TOWNSEND & STOCKTON LLP
Mailstop: IP Docketing - 22
1100 Peachtree Street
Suite 2800
Atlanta, GA 30309

OC000000102102301

Date Mailed: 09/06/2018

Receipt is acknowledged of this non-provisional patent application. The application will be taken up for examination in due course. Applicant will be notified as to the results of the examination. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

Inventor(s)

Angus Pacala, San Francisco, CA;
Mark Frichtl, San Francisco, CA;

Applicant(s)

Ouster, Inc., San Francisco, CA;

Assignment For Published Patent Application

Ouster, Inc., San Francisco, CA

Power of Attorney: None

Domestic Priority data as claimed by applicant

This application is a CON of 15/880,491 01/25/2018
which is a CON of 15/276,532 09/26/2016 PAT 9992477
which claims benefit of 62/232,222 09/24/2015

Foreign Applications for which priority is claimed (You may be eligible to benefit from the **Patent Prosecution Highway** program at the USPTO. Please see http://www.uspto.gov for more information.) - None.
Foreign application information must be provided in an Application Data Sheet in order to constitute a claim to foreign priority. See 37 CFR 1.55 and 1.76.

Permission to Access Application via Priority Document Exchange: Yes

Permission to Access Search Results: Yes

Applicant may provide or rescind an authorization for access using Form PTO/SB/39 or Form PTO/SB/69 as appropriate.

If Required, Foreign Filing License Granted: 09/05/2018

The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 16/046,643**

Projected Publication Date: 12/13/2018

Non-Publication Request: No

Early Publication Request: No
**** SMALL ENTITY ****
Title

OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS

Preliminary Class

370

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications: No

PROTECTING YOUR INVENTION OUTSIDE THE UNITED STATES

Since the rights granted by a U.S. patent extend only throughout the territory of the United States and have no effect in a foreign country, an inventor who wishes patent protection in another country must apply for a patent in a specific country or in regional patent offices. Applicants may wish to consider the filing of an international application under the Patent Cooperation Treaty (PCT). An international (PCT) application generally has the same effect as a regular national patent application in each PCT-member country. The PCT process **simplifies** the filing of patent applications on the same invention in member countries, but **does not result** in a grant of "an international patent" and does not eliminate the need of applicants to file additional documents and fees in countries where patent protection is desired.

Almost every country has its own patent law, and a person desiring a patent in a particular country must make an application for patent in that country in accordance with its particular laws. Since the laws of many countries differ in various respects from the patent law of the United States, applicants are advised to seek guidance from specific foreign countries to ensure that patent rights are not lost prematurely.

Applicants also are advised that in the case of inventions made in the United States, the Director of the USPTO must issue a license before applicants can apply for a patent in a foreign country. The filing of a U.S. patent application serves as a request for a foreign filing license. The application's filing receipt contains further information and guidance as to the status of applicant's license for foreign filing.

Applicants may wish to consult the USPTO booklet, "General Information Concerning Patents" (specifically, the section entitled "Treaties and Foreign Patents") for more information on timeframes and deadlines for filing foreign patent applications. The guide is available either by contacting the USPTO Contact Center at 800-786-9199, or it can be viewed on the USPTO website at http://www.uspto.gov/web/offices/pac/doc/general/index.html.

For information on preventing theft of your intellectual property (patents, trademarks and copyrights), you may wish to consult the U.S. Government website, http://www.stopfakes.gov. Part of a Department of Commerce initiative, this website includes self-help "toolkits" giving innovators guidance on how to protect intellectual property in specific countries such as China, Korea and Mexico. For questions regarding patent enforcement issues, applicants may call the U.S. Government hotline at 1-866-999-HALT (1-866-999-4258).

LICENSE FOR FOREIGN FILING UNDER

Title 35, United States Code, Section 184

Title 37, Code of Federal Regulations, 5.11 & 5.15

GRANTED

The applicant has been granted a license under 35 U.S.C. 184, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" followed by a date appears on this form. Such licenses are issued in all applications where the conditions for issuance of a license have been met, regardless of whether or not a license may be required as set forth in 37 CFR 5.15. The scope and limitations of this license are set forth in 37 CFR 5.15(a) unless an earlier license has been issued under 37 CFR 5.15(b). The license is subject to revocation upon written notification. The date indicated is the effective date of the license, unless an earlier license of similar scope has been granted under 37 CFR 5.13 or 5.14.

This license is to be retained by the licensee and may be used at any time on or after the effective date thereof unless it is revoked. This license is automatically transferred to any related applications(s) filed under 37 CFR 1.53(d). This license is not retroactive.

The grant of a license does not in any way lessen the responsibility of a licensee for the security of the subject matter as imposed by any Government contract or the provisions of existing laws relating to espionage and the national security or the export of technical data. Licensees should apprise themselves of current regulations especially with respect to certain countries, of other agencies, particularly the Office of Defense Trade Controls, Department of State (with respect to Arms, Munitions and Implements of War (22 CFR 121-128)); the Bureau of Industry and Security, Department of Commerce (15 CFR parts 730-774); the Office of Foreign AssetsControl, Department of Treasury (31 CFR Parts 500+) and the Department of Energy.

NOT GRANTED

No license under 35 U.S.C. 184 has been granted at this time, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" DOES NOT appear on this form. Applicant may still petition for a license under 37 CFR 5.12, if a license is desired before the expiration of 6 months from the filing date of the application. If 6 months has lapsed from the filing date of this application and the licensee has not received any indication of a secrecy order under 35 U.S.C. 181, the licensee may foreign file the application pursuant to 37 CFR 5.15(b).

SelectUSA

The United States represents the largest, most dynamic marketplace in the world and is an unparalleled location for business investment, innovation, and commercialization of new technologies. The U.S. offers tremendous resources and advantages for those who invest and manufacture goods here. Through SelectUSA, our nation works to promote and facilitate business investment. SelectUSA provides information assistance to the international investor community; serves as an ombudsman for existing and potential investors; advocates on behalf of U.S. cities, states, and regions competing for global investment; and counsels U.S. economic development organizations on investment attraction best practices. To learn more about why the United States is the best country in the world to develop technology, manufacture products, deliver services, and grow your business, visit http://www.SelectUSA.gov or call +1-202-482-6800.

PATENT APPLICATION FEE DETERMINATION RECORD

Substitute for Form PTO-875

Application or Docket Number: 16/046,643

APPLICATION AS FILED - PART I

FOR	(Column 1) NUMBER FILED	(Column 2) NUMBER EXTRA	SMALL ENTITY RATE($)	SMALL ENTITY FEE($)	OR	OTHER THAN SMALL ENTITY RATE($)	OTHER THAN SMALL ENTITY FEE($)
BASIC FEE (37 CFR 1.16(a), (b), or (c))	N/A	N/A	N/A	75		N/A	
SEARCH FEE (37 CFR 1.16(k), (i), or (m))	N/A	N/A	N/A	330		N/A	
EXAMINATION FEE (37 CFR 1.16(o), (p), or (q))	N/A	N/A	N/A	380		N/A	
TOTAL CLAIMS (37 CFR 1.16(i))	34 minus 20 =	* 14	x 50 =	700	OR		
INDEPENDENT CLAIMS (37 CFR 1.16(h))	4 minus 3 =	* 1	x 230 =	230			
APPLICATION SIZE FEE (37 CFR 1.16(s))	If the specification and drawings exceed 100 sheets of paper, the application size fee due is $310 ($155 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s).			0.00			
MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j))				0.00			
* If the difference in column 1 is less than zero, enter "0" in column 2.			TOTAL	1715		TOTAL	

APPLICATION AS AMENDED - PART II

		(Column 1) CLAIMS REMAINING AFTER AMENDMENT		(Column 2) HIGHEST NUMBER PREVIOUSLY PAID FOR	(Column 3) PRESENT EXTRA	SMALL ENTITY RATE($)	SMALL ENTITY ADDITIONAL FEE($)	OR	OTHER THAN SMALL ENTITY RATE($)	OTHER THAN SMALL ENTITY ADDITIONAL FEE($)
AMENDMENT A	Total (37 CFR 1.16(i))	*	Minus	**	=	x =		OR	x =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=	x =		OR	x =	
	Application Size Fee (37 CFR 1.16(s))									
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))							OR		
						TOTAL ADD'L FEE		OR	TOTAL ADD'L FEE	

		(Column 1) CLAIMS REMAINING AFTER AMENDMENT		(Column 2) HIGHEST NUMBER PREVIOUSLY PAID FOR	(Column 3) PRESENT EXTRA	RATE($)	ADDITIONAL FEE($)	OR	RATE($)	ADDITIONAL FEE($)
AMENDMENT B	Total (37 CFR 1.16(i))	*	Minus	**	=	x =		OR	x =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=	x =		OR	x =	
	Application Size Fee (37 CFR 1.16(s))									
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))							OR		
						TOTAL ADD'L FEE		OR	TOTAL ADD'L FEE	

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20".
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3".
The "Highest Number Previously Paid For" (Total or Independent) is the highest found in the appropriate box in column 1.

Doc Code: PA..
Document Description: Power of Attorney

PTO/AIA/82A (07-13)
Approved for use through 01/31/2018. OMB 0651-0035
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

TRANSMITTAL FOR POWER OF ATTORNEY TO ONE OR MORE REGISTERED PRACTITIONERS

NOTE: This form is to be submitted with the Power of Attorney by Applicant form (PTO/AIA/82B) to identify the application to which the Power of Attorney is directed, in accordance with 37 CFR 1.5, unless the application number and filing date are identified in the Power of Attorney by Applicant form. If neither form PTO/AIA/82A nor form PTO/AIA82B identifies the application to which the Power of Attorney is directed, the Power of Attorney will not be recognized in the application.

Application Number	16/046,643
Filing Date	July 26, 2018
First Named Inventor	Angus Pacala
Title	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
Art Unit	2414
Examiner Name	Not yet assigned
Attorney Docket Number	103033-P001USC2-1096583

SIGNATURE of Applicant or Patent Practitioner

Signature	/William L. Shaffer/	Date (Optional)	
Name	William L. Shaffer	Registration Number	37234
Title (if Applicant is a juristic entity)			
Applicant Name (if Applicant is a juristic entity)			

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4(d) for signature requirements and certifications. If more than one applicant, use multiple forms.

☑ *Total of 1 forms are submitted.

This collection of information is required by 37 CFR 1.131, 1.32, and 1.33. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 3 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

16/046,643	July 26, 2018

Electronic Acknowledgement Receipt	
EFS ID:	33826242
Application Number:	16046643
International Application Number:	
Confirmation Number:	1720
Title of Invention:	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
First Named Inventor/Applicant Name:	Angus Pacala
Customer Number:	20350
Filer:	William Leland Shaffer/La Renda Meyer
Filer Authorized By:	William Leland Shaffer
Attorney Docket Number:	103033-P001USC2-1096583
Receipt Date:	25-SEP-2018
Filing Date:	26-JUL-2018
Time Stamp:	18:49:02
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Power of Attorney	Transmittal_PowerofAttorney_P001USC2.pdf	236271 c90e5aee810667f4214284d5c279ae515b91337c	no	2

Warnings:

Information:	
Total Files Size (in bytes):	236271

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

Doc Code: PA..
Document Description: Power of Attorney

PTO/AIA/82A (07-13)
Approved for use through 01/31/2018. OMB 0651-0035
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

TRANSMITTAL FOR POWER OF ATTORNEY TO ONE OR MORE REGISTERED PRACTITIONERS

NOTE: This form is to be submitted with the Power of Attorney by Applicant form (PTO/AIA/82B) to identify the application to which the Power of Attorney is directed, in accordance with 37 CFR 1.5, unless the application number and filing date are identified in the Power of Attorney by Applicant form. If neither form PTO/AIA/82A nor form PTO/AIA82B identifies the application to which the Power of Attorney is directed, the Power of Attorney will not be recognized in the application.

Application Number	16/046,643
Filing Date	July 26, 2018
First Named Inventor	Angus Pacala
Title	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
Art Unit	2414
Examiner Name	Not yet assigned
Attorney Docket Number	103033-P001USC2-1096583

SIGNATURE of Applicant or Patent Practitioner

Signature	/William L. Shaffer/	Date (Optional)	
Name	William L. Shaffer	Registration Number	37234
Title (if Applicant is a juristic entity)			
Applicant Name (if Applicant is a juristic entity)			

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4(d) for signature requirements and certifications. If more than one applicant, use multiple forms.

☑ *Total of 1 forms are submitted.

This collection of information is required by 37 CFR 1.131, 1.32, and 1.33. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 3 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

16/046,643 July 26, 2018

Electronic Acknowledgement Receipt	
EFS ID:	33826286
Application Number:	16046643
International Application Number:	
Confirmation Number:	1720
Title of Invention:	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
First Named Inventor/Applicant Name:	Angus Pacala
Customer Number:	20350
Filer:	William Leland Shaffer
Filer Authorized By:	
Attorney Docket Number:	103033-P001USC2-1096583
Receipt Date:	25-SEP-2018
Filing Date:	26-JUL-2018
Time Stamp:	18:52:55
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Power of Attorney	Transmittal_PowerofAttorney_P001USC2.pdf	236271 c90e5aee810667f4214284d5c279ae515b91337c	no	2

Warnings:

Information:	
Total Files Size (in bytes):	236271

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

Doc Code: PA..
Document Description: Power of Attorney

PTO/AIA/82A (07-13)
Approved for use through 01/31/2018. OMB 0651-0035
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

TRANSMITTAL FOR POWER OF ATTORNEY TO ONE OR MORE REGISTERED PRACTITIONERS

NOTE: This form is to be submitted with the Power of Attorney by Applicant form (PTO/AIA/82B) to identify the application to which the Power of Attorney is directed, in accordance with 37 CFR 1.5, unless the application number and filing date are identified in the Power of Attorney by Applicant form. If neither form PTO/AIA/82A nor form PTO/AIA82B identifies the application to which the Power of Attorney is directed, the Power of Attorney will not be recognized in the application.

Application Number	16/046,643
Filing Date	July 26, 2018
First Named Inventor	Angus Pacala
Title	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
Art Unit	2414
Examiner Name	Not yet assigned
Attorney Docket Number	103033-P001USC2-1096583

SIGNATURE of Applicant or Patent Practitioner

Signature	/William L. Shaffer/	Date (Optional)	
Name	William L. Shaffer	Registration Number	37234
Title (if Applicant is a juristic entity)			
Applicant Name (if Applicant is a juristic entity)			

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4(d) for signature requirements and certifications. If more than one applicant, use multiple forms.

☑ *Total of 1 forms are submitted.

This collection of information is required by 37 CFR 1.131, 1.32, and 1.33. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 3 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

Doc Code: PA..
Document Description: Power of Attorney

PTO/AIA/82B (07-13)
Approved for use through 11/30/2014. OMB 0651-0051
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number

POWER OF ATTORNEY BY APPLICANT

I hereby revoke all previous powers of attorney given in the application identified in either the attached transmittal letter or the boxes below.

Application Number	Filing Date
16/046,643	July 26, 2018

(Note: The boxes above may be left blank if information is provided on form PTO/AIA/82A.)

☑ I hereby appoint the Patent Practitioner(s) associated with the following Customer Number as my/our attorney(s) or agent(s), and to transact all business in the United States Patent and Trademark Office connected therewith for the application referenced in the attached transmittal letter (form PTO/AIA/82A) or identified above: 20350

OR

☐ I hereby appoint Practitioner(s) named in the attached list (form PTO/AIA/82C) as my/our attorney(s) or agent(s), and to transact all business in the United States Patent and Trademark Office connected therewith for the patent application referenced in the attached transmittal letter (form PTO/AIA/82A) or identified above. (Note: Complete form PTO/AIA/82C.)

Please recognize or change the correspondence address for the application identified in the attached transmittal letter or the boxes above to:

☑ The address associated with the above-mentioned Customer Number

OR

☐ The address associated with Customer Number:

OR

Firm or Individual Name					
Address					
City		State		Zip	
Country					
Telephone		Email			

I am the Applicant (if the Applicant is a juristic entity, list the Applicant name in the box):

Ouster, Inc.

☐ Inventor or Joint Inventor (title not required below)

☐ Legal Representative of a Deceased or Legally Incapacitated Inventor (title not required below)

☑ Assignee or Person to Whom the Inventor is Under an Obligation to Assign (provide signer's title if applicant is a juristic entity)

☐ Person Who Otherwise Shows Sufficient Proprietary Interest (e.g., a petition under 37 CFR 1.46(b)(2) was granted in the application or is concurrently being filed with this document) (provide signer's title if applicant is a juristic entity)

SIGNATURE of Applicant for Patent

The undersigned (whose title is supplied below) is authorized to act on behalf of the applicant (e.g., where the applicant is a juristic entity).

Signature	Mark Frichtl	Date (Optional)	2017-10-04
Name	Mark Frichtl		
Title	CTO		

NOTE: Signature - This form must be signed by the applicant in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications. If more than one applicant, use multiple forms.

☑ Total of forms are submitted.

This collection of information is required by 37 CFR 1.131, 1.32, and 1.33. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 3 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

Electronic Acknowledgement Receipt	
EFS ID:	33826308
Application Number:	16046643
International Application Number:	
Confirmation Number:	1720
Title of Invention:	OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS
First Named Inventor/Applicant Name:	Angus Pacala
Customer Number:	20350
Filer:	William Leland Shaffer
Filer Authorized By:	
Attorney Docket Number:	103033-P001USC2-1096583
Receipt Date:	25-SEP-2018
Filing Date:	26-JUL-2018
Time Stamp:	18:55:59
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Power of Attorney	Transmittal_with_POA_P001USC2.pdf	240879 bbb5d513c3fb186b879fd321210c69089ba b1da8	no	2

Warnings:

Information:	
Total Files Size (in bytes):	240879

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.
National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.
New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
16/046,643	07/26/2018	Angus Pacala	103033-P001USC2-1096583

CONFIRMATION NO. 1720

POA ACCEPTANCE LETTER

20350
KILPATRICK TOWNSEND & STOCKTON LLP
Mailstop: IP Docketing - 22
1100 Peachtree Street
Suite 2800
Atlanta, GA 30309

OC000000102647748

Date Mailed: 09/28/2018

NOTICE OF ACCEPTANCE OF POWER OF ATTORNEY

This is in response to the Power of Attorney filed 09/25/2018.

The Power of Attorney in this application is accepted. Correspondence in this application will be mailed to the above address as provided by 37 CFR 1.33.

Questions about the contents of this notice and the requirements it sets forth should be directed to the Office of Data Management, Application Assistance Unit, at **(571) 272-4000** or **(571) 272-4200** or **1-888-786-0101**.

/hsarwari/

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
16/046,643	07/26/2018	Angus Pacala	103033-P001USC2-1096583

CONFIRMATION NO. 1720

20350
KILPATRICK TOWNSEND & STOCKTON LLP
Mailstop: IP Docketing - 22
1100 Peachtree Street
Suite 2800
Atlanta, GA 30309

PUBLICATION NOTICE



Title:OPTICAL IMAGING SYSTEM WITH A PLURALITY OF SENSE CHANNELS

Publication No.US-2018-0359460-A1
Publication Date:12/13/2018

NOTICE OF PUBLICATION OF APPLICATION

The above-identified application will be electronically published as a patent application publication pursuant to 37 CFR 1.211, et seq. The patent application publication number and publication date are set forth above.

The publication may be accessed through the USPTO's publically available Searchable Databases via the Internet at www.uspto.gov. The direct link to access the publication is currently http://www.uspto.gov/patft/.

The publication process established by the Office does not provide for mailing a copy of the publication to applicant. A copy of the publication may be obtained from the Office upon payment of the appropriate fee set forth in 37 CFR 1.19(a)(1). Orders for copies of patent application publications are handled by the USPTO's Public Records Division. The Public Records Division can be reached by telephone at (571) 272-3150 or (800) 972-6382, by facsimile at (571) 273-3250, by mail addressed to the United States Patent and Trademark Office, Public Records Division, Alexandria, VA 22313-1450 or via the Internet.

In addition, information on the status of the application, including the mailing date of Office actions and the dates of receipt of correspondence filed in the Office, may also be accessed via the Internet through the Patent Electronic Business Center at www.uspto.gov using the public side of the Patent Application Information and Retrieval (PAIR) system. The direct link to access this status information is currently https://portal.uspto.gov/pair/PublicPair. Prior to publication, such status information is confidential and may only be obtained by applicant using the private side of PAIR.

Further assistance in electronically accessing the publication, or about PAIR, is available by calling the Patent Electronic Business Center at 1-866-217-9197.

Office of Data Managment, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Not for submission under 37 CFR 1.99)		
	Application Number	16/046,643
	Filing Date	July 26, 2018
	First Named Inventor	Angus Pacala
	Art Unit	2414
	Examiner Name	Not yet assigned
	Attorney Docket Number	103033-P001USC2-1096583

U.S. PATENTS

Examiner Initial*	Cite No	Patent Number	Kind Code[1]	Issue Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
	1.	10183541	B2	01-22-2019	Van Den Bossche, et al.	
	2.	9551791	B2	01-24-2017	Van Den Bossche, et al.	

U.S. PATENT APPLICATION PUBLICATIONS

Examiner Initial*	Cite No	Publication Number	Kind Code[1]	Publication Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
	3.	20180299554	A1	10-18-2018	Dirk van Dyck	

FOREIGN PATENT DOCUMENTS

Examiner Initial*	Cite No	Foreign Document Number[3]	Country Code[2]	Kind Code[4]	Publication Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines where Relevant Passages or Relevant Figures Appear	T[5]
	4.	3045935	EP	A1	07-20-2016	XenomatiX BVBA		
	5.	3316000	EP	A1	05-02-2018	Xenomatix Nv		
	6.	2018065428	WO	A3	04-12-2018	Xenomatix Nv		
	7.	2018065427	WO	A1	04-12-2018	Xenomatix Nv		
	8.	2018065429	WO	A1	04-12-2018	Xenomatix Nv		

INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Not for submission under 37 CFR 1.99)		
	Application Number	16/046,643
	Filing Date	July 26, 2018
	First Named Inventor	Angus Pacala
	Art Unit	2414
	Examiner Name	Not yet assigned
	Attorney Docket Number	103033-P001USC2-1096583

	9.	2018065426	WO	A1	04-12-2018	Xenomatix Nv		
	10.	2018122415	WO	A1	07-05-2018	Xenomatix Nv		
	11.	2018197441	WO	A1	11-01-2018	Xenomatix Nv		

NON-PATENT LITERATURE DOCUMENTS			
Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T[5]

EXAMINER SIGNATURE			
Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document.
[4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

I hereby certify that this correspondence is being filed via EFS-Web with the United States Patent and Trademark Office on March 21, 2019.

KILPATRICK TOWNSEND & STOCKTON LLP

By: /La Renda Meyer/

PATENT
Attorney Docket No.: 103033-1096583-P001USC2
Client Ref. No.: P001USC2

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	Confirmation No.: 1720
Angus Pacala	Examiner: Not yet assigned
Application No.: 16/046,643	Technology Center/Art Unit: 2414
Filed: July 26, 2018	
For: OPTICAL SYSTEM FOR COLLECTING DISTANCE INFORMATION WITHIN A FIELD	INFORMATION DISCLOSURE STATEMENT
Customer No.: 20350	

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Commissioner:

The references cited on attached form PTO/SB/08A are being called to the attention of the Examiner. In accordance with the provisions of 37 CFR §1.98(a)(2), copies of any cited U.S. Patents and U.S. Patent Application Publications are not provided. Copies of the references are not enclosed.

It is respectfully requested that the cited references be expressly considered during the prosecution of this application, and the references be made of record therein and appear among the "references cited" on any patent to issue therefrom.

As provided for by 37 CFR §1.97(g) and (h), no inference should be made that the information and references cited are prior art merely because they are in this statement and no

representation is being made that a search has been conducted or that this statement encompasses all the possible relevant information. This Information Disclosure Statement is being filed before the mailing date of the first Office Action on the merits.

Applicant believes that no fee is required for submission of this statement. However, if any additional fees are due for the submission of this Information Disclosure Statement, please deduct those fees from Deposit Account No. 20-1430.

Respectfully submitted,

/ William L. Shaffer /

William L. Shaffer
Registration No. 37,234

KILPATRICK TOWNSEND & STOCKTON LLP

Attachment

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
01 November 2018 (01.11.2018)

W!P O | PCT

(10) International Publication Number
WO 2018/197441 A1

(51) International Patent Classification:
G01S 17/10 (2006.01) *G01S 7/486* (2006.01)
G01S 17/89 (2006.01)

(21) International Application Number:
PCT/EP2018/060391

(22) International Filing Date:
23 April 2018 (23.04.2018)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
17167660.4 23 April 2017 (23.04.2017) EP

(71) Applicant: **XENOMATIX NV** [BE/BE]; Esperantolaan 4, B-3001 Leuven (BE).

(72) Inventors: **VAN DYCK, Dirk;** Kleine Grippe 37, B-2630 Aartselaar (BE). **PAESEN, Rik;** Helstraat 82, B-3590 Diepenbeek (BE).

(74) Agent: **IPLODGE BVBA;** Technologielaan 9, B-3001 Heverlee (BE).

(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,

(54) **Title:** A PIXEL STRUCTURE

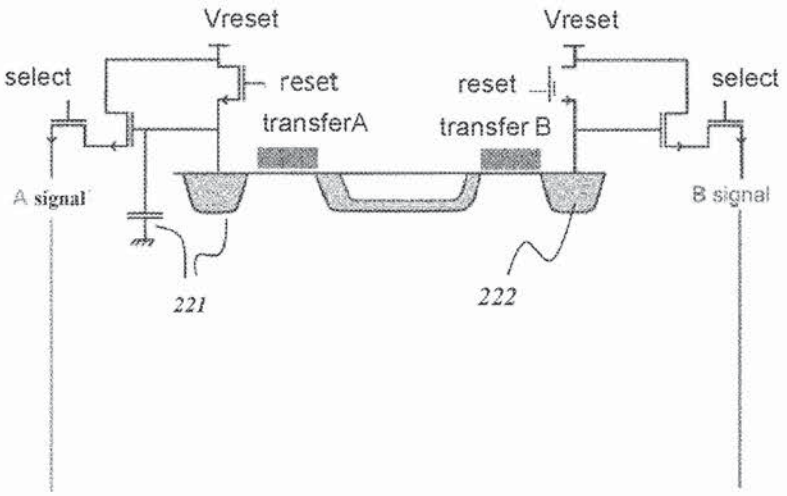


Fig. 6

(57) **Abstract:** The present invention pertains to a pixel for use in a system for determining a distance to an object by range gating, said pixel comprising: a first charge storage well (221) and a second charge storage well (222) for accumulating electrical charges representative of amounts of light impinging on said pixel during respective sets of exposure intervals, wherein said first charge storage well (221) has a charge capacity that is at least 50% greater than a charge capacity of said second charge storage well (222). The invention also pertains to a range gating system comprising such a pixel.

WO 2018/197441 A1

[Continued on nextpage]

TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

A pixel structure

Field of the Invention

The present invention pertains to the field of pixels, in particular pixels for use in imaging systems for determining a distance to an object on the basis of time-of-flight information obtained by range gating.

Background

United States patent no. 8,792,087 B2 to Andreas Spickerman et al. discloses a device in which at least two different transfer gates which couple a photoactive region to at least two different evaluating capacities are driven during different drive intervals so that charge carriers generated during the drive intervals by a radiation pulse reflected from the object of measurement and/or by ambient radiation can be transported from the photoactive region to the evaluating capacities each coupled to the at least two transfer gates. Another transfer gate is driven during a time outside the drive intervals of the at least two transfer gates to connect the photoactive region to a reference potential terminal acting as a charge carrier sink during the time outside the drive intervals of the at least two transfer gates.

It is a disadvantage of the system known from US 8,702,087 B2 that the pixels get saturated by reflections from objects at short distances from the sensor.

United States patent application publication no. US 2007/158770 A1 to Shoji Kawahito, discloses a range-finding image sensor based upon measurement of reflection time of light with reduced fabrication processes compared to standard CMOS manufacturing procedures. An oxide film is formed on a silicon substrate, and two photo-gate electrodes for charge-transfer are provided on the oxide film. Floating diffusion layers are used to convert charges to electronic potential, a mechanism traditionally inherited from

the legacy technology of Charged Coupled Devices (CCD). Extra transistors are provided for resetting and a diffusion layer to provide a given reset voltage.

It is a disadvantage of the pixel disclosed in US 2007/158770 A1 that it uses non-standard technology and that the pixel design does not allow the addition of additional wells without sacrificing active surface area of the pixel. This is suboptimal for usage in sensor systems with ultra low power lasers requiring large operational range. The used process is not commonly available in standard CMOS processes, which reduces this concept's applicability and its ability to be produced at an affordable cost in large volumes.

The range of a sensor based on such a design is also limited at the near end by saturation of the pixels by the strong reflections of projected light.

The saturation of pixels when sensing short-range reflections, or highly reflective objects such as traffic signs, license plates, etc., is especially problematic when the pixels are used in sensors for automotive applications, as is the purpose of the pixel according to the present invention, because Advanced Driver Assistance Systems (ADAS) and self-driving cars require high accuracy at short range. Moreover, in this application domain, accuracy at longer ranges, the ability to operate in bright ambient light conditions, and the requirement of compactness (requiring the use of solid-state semiconductor components) must not be sacrificed for the requirement of short-range accuracy.

It is therefore an object of embodiments of the present invention to overcome the short-range saturation problem for pixels used in range-gating based imaging systems by proposing a different pixel architecture .

Unpublished European patent application no. EP15191288.8, dated 23 October 2015, in the name of the present applicant, describes a

system for determining a distance to an object comprising: a solid-state light source arranged for projecting a pattern of spots of laser light towards the object in a sequence of pulses; a detector comprising a plurality of picture elements, the detector being configured for detecting light representing the pattern of spots as reflected by the object in synchronization with said sequence of pulses; and processing means configured to calculate the distance to the object as a function of exposure values generated by said picture elements in response to said detected light; wherein the picture elements are configured to generate said exposure values by accumulating, for each pulse of said sequence, a first amount of electrical charge representative of a first amount of light reflected by said object during a first predetermined time window and a second electrical charge representative of a second amount of light reflected by said object during a second predetermined time window, said second predetermined time window occurring after said first predetermined time window. Each of the plurality of picture elements may comprise at least two charge storage wells, and the detecting of the first amount of light and said detecting of said second amount of light occurs at respective ones of said at least two charge storage wells. EP15191288.8 does not describe a solution to the short-range saturation problem.

In a similar system, unpublished European patent application no. EP16192105 .1, dated 3 October 2016, in the name of the present applicant, describes that for given total pixel space, the saturation problem can be mitigated by using an asymmetric well arrangement, in which the photon capacity represented by the first well is increased, and the photon capacity represented by the second well is decreased. If the increase and decrease are balanced, an increase of the dynamic range can be obtained at no additional pixel surface cost, thus maintaining the same resolution. EP16192105.1 does not describe any specific ratios between the photon capacity represented by the first well and the photon capacity represented by the second well.

Summary of the Invention

According to an aspect of the present invention, there is provided a pixel for use in a system for determining a distance to an object by range gating, said pixel comprising a first charge storage well and a second charge storage well for accumulating electrical charges representative of amounts of light reflected by said object and impinging on said pixel during respective sets of exposure intervals, and a third charge storage well, wherein said first charge storage well has a charge capacity that is at least 50% greater than a charge capacity of said second charge storage well, and wherein said third charge storage well has a smaller charge storage capacity than said first charge storage well and said second charge storage well .

The invention is based on the insight of the inventors that in certain systems, such as the range-gating based imaging system described in more detail below, it is advantageous to have a dual-well pixel (the presence of additional wells is not excluded) whereby one of the charge storage wells has a substantially larger charge capacity than the other charge storage well. The term "well" may designate a single capacitance (electron capacity) produced in a semiconductor circuit by appropriate techniques, or a multitude of interconnected capacities acting jointly as a single storage unit, arranged for example as a cascade. A pixel of this type is particularly useful where the physics of the situation in which the pixel is deployed lead to a predictable asymmetry in the amount of charge to be stored in the different wells, as is the case in a time-of-f light based measuring system requiring high accuracy and a large distance range, resulting in a large photon span.

To the extent that the pixel of the present invention resolves the short-range saturation problem, it removes the need for other work-arounds that extend the operating range at the short end. For example, in systems relying on multiple consecutive measurements for multiple sub-ranges of the desired range (multi-frame systems,

where the pulse width varies in function of the distance range to be covered by each frame), the pixel according to the present invention allows for a reduction of the number of measurements (individual frames required to cover the full intended operating range), thus improving the temporal resolution of the sensor.

The pixel according to the present invention preferably comprises a photosensitive element compatible with standard solid-state (semiconductor) circuit production processes.

A third well is provided to perform a variety of functions, provided that it is operated according to a timing scheme that takes into account the timing of the operation of the other wells. In a distance sensing system in which the first well and the second well perform the basic range gating, as described in more detail below, the functions of the third well may include receiving the additional charges that are generated in response to photons arriving from a long-range highly reflective objects (such as a traffic sign or a license plate, outside the time slots in which the first well and the second well are active), producing a regular 2-dimensional image of the scenery (outside the time slots in which the reflections of the projected light arrive, optionally in synchronization with a wide-angle flash light for illuminating the scenery which may consist of a VCSEL array with a diffuser), or performing background light subtraction (by subtracting from the charge levels accumulated in the first well and the second well, an amount of charge accumulated in the third well outside the time slots in which the reflections of the projected light arrive).

The third charge storage well may have a significantly smaller charge storage capacity than the first charge storage well and the second charge storage well, if it is only used for capturing background light, as the background light arriving at the pixel array will typically have been strongly attenuated by the ambient light reduction filters that are preferably provided in a distance sensing system. If the third charge storage well is intended to be

used for acquiring 2D images with additional lighting of the scenery (e.g., by means of a flash light) or for capturing reflections from out-of-range highly reflective objects, it may be dimensioned to a similar storage capacity as the first or second charge storage well .

In an embodiment, said pixel further comprises circuitry allowing said pixel to switch between a charging mode, in which light impinging on said pixel causes said first charge storage well or said second charge storage well to increase a stored amount of charge, and a discharging mode, in which light impinging on said pixel causes said first charge storage well or said second charge storage well to decrease a stored amount of charge.

This embodiment is based on the insight of the inventors that in a pulsed system, the "pulse on" intervals are characterized by the presence of projected light and background light, while the part of the "pulse off" intervals occurring after the arrival of the pulse reflection are characterized by the presence of background light only. The inventors developed a method in which by switching the pixel into a "discharging" mode after each exposure that corresponds with a "pulse on" interval, for a period that is equal to the exposure period, the remaining charge in each storage well will be equal to the captured reflection of the projected light without the background light component.

It is an advantage of this embodiment of the pixel according to the present invention that it can be used in a method for subtracting background light from pixels in a pixel array, e.g. as used in a range gating sensor. In particular, it enables a method of subtracting background light from an exposure value of a first pixel in an imaging array, said first pixel receiving a reflection of a spot from a scenery illuminated by a periodically pulsed pattern of spots, said periodically pulsed pattern comprising in alternation an illuminated phase and a non-illuminated phase, the method comprising: accumulating in said first pixel a charge in proportion to a first quantity of incident light, received in said

first pixel while detecting said spot during a predetermined amount of time; and decreasing said charge in proportion to a second quantity of incident light received during said predetermined amount of time in absence of said spot.

In an embodiment, said pixel further comprises circuitry allowing photocharges that are generated when an active one of said first charge storage well and said second charge storage well is filled to capacity, to be to deviated to a charge sink without entering a storage well of an adjacent pixel.

It is an advantage of this embodiment that blooming can be avoided, such that high spatial accuracy of spot detection in an array of pixels can be maintained even when individual pixels get saturated, by avoiding spill-over effects to neighboring pixels that can still be used for background measurements or for acquiring a regular 2D image.

In an embodiment, the pixel according to the present invention further comprises a fourth charge storage well.

According to an aspect of the present invention, there is provided an imaging array comprising a plurality of pixels as described above .

According to an aspect of the present invention, there is provided a system for determining a distance to an object comprising: a solid-state light source arranged for projecting a pattern of spots, preferably discrete spots, of light towards the object in a sequence of pulses, preferably a periodically repeated sequence of pulses; a detector comprising an imaging array as described above, the detector being configured for detecting light representing the pattern of spots as reflected by the object in synchronization with said sequence of pulses; and processing means configured to calculate the distance to the object as a function of exposure values generated by said pixels in response to said detected light; wherein the pixels of the imaging array are configured to

generate said exposure values by accumulating, for all pulses of said sequence, a first amount of electrical charge representative of a first amount of light reflected by said object during a first predetermined time window and a second electrical charge representative of a second amount of light reflected by said object during a second predetermined time window, said second predetermined time window occurring after said first predetermined time window, wherein the detecting of the first amount of light and the detecting of said second amount of light occurs at said first charge storage well and at said second charge storage well, respectively .

The solid-state light source is preferably a semiconductor light source. The projected discrete spots are preferably spots of laser light .

The system according to the present invention relies on the same physical principles as direct time-of-flight based ranging systems, viz. the fact that light always takes a certain amount of time to travel a given distance. However, the present invention uses range gating to determine the distance travelled by a light pulse that has been transmitted and subsequently reflected by a target object. The present invention is *inter alia* based on the insight of the inventors that by combining range gating, an at least partially simultaneous spot pattern projection (based on a novel illumination scheme) and a low-power semiconductor light source, a substantially miniaturized, full solid state and energy-efficient long-range distance detection method can be obtained. The term "pattern" as used herein refers to a spatial distribution of simultaneously projected spots, preferably discrete (non-overlapping) spots. In order to determine the position of the detected spot reflection in three-dimensional space, it is necessary to combine the distance information obtained from the ranging step with angular information to fix the remaining two spatial coordinates. A camera comprising a pixel array and suitably arranged optics can be used to provide the additional

angular information, by identifying the pixel in which the reflection is detected.

Embodiments of the present invention are based on the further insight of the inventors that in order to be able to use spot patterns generated by solid-state semiconductor light sources in a LIDAR system at the desired ranges, a way to circumvent the optical power limitations is needed. The inventors have found that by prolonging the pulse duration and by integrating the reflected energy of multiple VCSEL-generated light pulses within at least two semiconductor sensor wells or within at least two pixels, followed by a single read-out of the integrated charge, a solid-state LIDAR system can be obtained with a significantly greater operating range than is currently possible with solid-state implementations. In addition, multiple sequences of light pulses, using a different pulse duration in each sequence, may be combined to cover a larger distance range than would be possible with a single sequence. Hereinafter, the term "storage" will be used to designate the well or the pixel in which charge is accumulated in response to the detection of photons.

It is an advantage of the system according to the present invention that the solid-state light source and the solid-state sensor (such as a CMOS sensor, a CCD sensor or the like) may be integrated on the same semiconductor substrate. The solid-state light source may comprise a VCSEL array or a laser with a grating adapted to produce the desired pattern.

Moreover, by assessing the reflected light energy detected in two consecutive time windows, and normalizing for the total accumulated charge in the two consecutive windows, the impact of varying reflectivity of the object under study and the contribution of ambient light can adequately be accounted for in the distance calculation algorithm.

Finally, by using the pixel as described above, the system according the present invention is less susceptible to saturation

of the charge storage wells due to intense reflections received from objects at short range.

In an embodiment, the system is configured to perform the projecting and the detecting for at least two consecutive sequences of pulses, each of the sequences being operated with a different duration of the first predetermined time window and the second predetermined time window.

This embodiment is further based on the insight of the inventors that the range of the system can be improved by splitting up the sensing of the full range over multiple frames (i.e., multiple sequences of pulses), each of which allows computation of the distance for a different range by virtue of operating with different timing parameters (the first predetermined time window and the second predetermined time window) .

A judicious choice of these operating parameters can ensure that in each frame, the number of reflected photons expected to be detected for the maximal distance of the desired range corresponds to an amount of charge that can be reliably read out from the charge storage well. On the other hand, the nearest point at which accurate measurements can be carried out is determined by the number of photons that will saturate the capacity of the pixels. The ratio between the minimal detectable number of photons and the maximal number of photons that can be received without saturation determines the distance range that can be spanned in a single frame .

In an embodiment of the system according to the present invention, the imaging array is further adapted to perform 2D video image acquisition .

The 2D video image acquisition may be performed in the same frames in which the range gating takes place, by employing the third charge storage well and/or a fourth charge storage well or by employing pixels of the pixel array that are not being illuminated

by reflections of the projected light spots. Additionally or alternatively, the 2D video image acquisition may be performed in the other frames that the frames in which the range gating takes place, optionally in synchronization with a global illumination of the scenery.

Brief Description of the Figures

These and other aspects and advantages of the present invention will now be described in more detail with reference to the accompanying drawings , in which:

Figure 1 represents a flow chart of the range gating process applied by an embodiment of the system according to the present invention, in which the pixel according to the present invention may be used;

Figure 2 schematically represents an embodiment of the system according to the present invention, in which the pixel according to the present invention may be used;

Figures 3a-c present timing schemes of the range gating process applied by an embodiment of the system according to the present invention, to illustrate the operation of the two wells involved in range gating;

Figure 4 schematically represents an embodiment of the pixel according to the present invention;

Figure 5 schematically represents an embodiment of the pixel according to the present invention, showing a first way of obtaining the asymmetry of the wells;

Figure 6 schematically represents an embodiment of the pixel according to the present invention, showing a second way of obtaining the asymmetry of the wells; and

Figures 7a-7g represent timing diagrams for light projection and detection in embodiments of the present invention, to illustrate the operation of additional wells.

Throughout the figures, like numerals are used to refer to like elements .

Detailed Description of Embodiments

The inventors have found that the pixel array according to the present invention can advantageously be applied in a novel type of ranging system which aims to achieve the same power/performance characteristics with a compact, semiconductor based time-of-flight based system. Accordingly, an aspect of the present invention concerns a ranging system comprising a plurality of pixels as will be described below, arranged in a pixel array.

In this aspect of the invention, the limitations of the existing LIDAR-based systems are overcome by changing the way the time-of-flight based system operates. The total amount of light energy emitted for each time-of-flight measurement (and thus, the number of photons available for detection at the detector for each time-of-flight measurement) may be increased by increasing the duration of individual pulses and by producing a virtual "composite pulse", consisting of a sequence of a large number of individual pulses. This bundling of extended pulses allowed the inventors to obtain the required amount of light energy (photons) for the desired operational range with low-power solid-state lasers, such as VCSELs .

Where an individual pulse of pre-existing LIDAR systems may have a duration of 1 ns, the presently described systems benefit from a substantially longer pulse duration to partially compensate for the relatively low power level of semiconductor lasers such as VCSELs; in embodiments of the present invention, individual pulses within a sequence may have an exemplary duration of 1 µs (this is one possible value, chosen here to keep the description clear and

simple; more generally, in embodiments of the present invention, the pulse duration may for example be 500 ns or more, preferably 750 ns or more, most preferably 900 ns or more) . In an exemplary system according to the present invention, a sequence may consist of 1000 pulse cycles, thus adding up to a duration of 1 ms. Given the fact that light would need approximately 0.66 µs to travel to a target at a distance of 100 m and back to the detector, it is possible to use composite pulses of this duration for ranging at distance of this order of magnitude; the skilled person will be able to adjust the required number of pulse cycles in function of the selected pulse width and the desired range. The detection of the sequence preferably comprises detecting the individual pulses in synchronization with the VCSEL-based light source, and accumulating the charges generated in response to the incoming photons at the pixel well level for the entire sequence prior to read-out. The term "exposure value" is used hereinafter to designate the value representative of the charge (and thus of the amount of light received at the pixel) integrated over the sequence. The sequence emission and detection may be repeated periodically .

The ranging system of the present invention operates by using range gating. Range gated imagers integrate the detected power of the reflection of the emitted pulse for the duration of the pulse. The amount of temporal overlap between the pulse emission window and the arrival of the reflected pulse depends on the return time of the light pulse, and thus on the distance travelled by the pulse. Thus, the integrated power is correlated to the distance travelled by the pulse. The present invention uses the principle of range gating, as applied to the sequences of pulses described hereinabove. In the following description, the integration of individual pulses of a sequence at the level of a picture element to obtain a measurement of the entire sequence is implicitly understood.

Figure 1 represents a flow chart of an applicable ranging method. Without loss of generality, the ranging method is described with

reference to a range gating algorithm. In a first time window **10**, the method comprises projecting **110** a pattern of spots of laser light (e.g. a regular or an irregular spatial pattern of spots) from a light source comprising a solid-state light source **210** onto any objects in the targeted area of the scenery. The spatial pattern is repeatedly projected in a sequence of pulses.

As indicated above, the solid-state light source may comprise a VCSEL array or a laser with a grating adapted to produce the desired pattern. In order for the system to operate optimally, even at long ranges and with high levels of ambient light (e.g., in daylight) , a VCSEL for use in embodiments of the present invention is preferably arranged to emit a maximum optical power per spot per unit of area. Thus, lasers with a good beam quality (low M2-factor) are preferred. More preferably, the lasers should have a minimal wavelength spread; a particularly low wavelength spread can be achieved with monomode lasers. Thus, substantially identical pulses can reproducibly be generated, with the necessary spatial and temporal accuracy.

During the same time window in which a pulse is emitted, or in a substantially overlapping time window, a first amount of light representing the pattern of spots as reflected by the object of interest is detected **120** at a detector, which is preferably arranged as near as possible to the light source. The synchronicity or near synchronicity between the projection **110** of the spot pattern and the first detection **120** of its reflection, is illustrated in the flow chart by the side-by-side arrangement of these steps. In a subsequent second predetermined time window **20**, a second amount of light representing the reflected light spot is detected **130** at the detector. During this second window **20**, the solid-state light source is inactive. The distance to the object can then be calculated **140** as a function of the first amount of reflected light and the second amount of reflected light.

The first predetermined time window **10** and the second predetermined time window **20** are preferably back-to-back windows

of substantially equal duration, to facilitate noise and ambient light cancellation by subtracting one of the detected amounts from the other one. An exemplary timing scheme will be described in more detail below in conjunction with Figure 3.

The detector comprises a pixel array as described above with adequate optics arranged to project an image of the scenery (including the illuminated spots) onto the picture element.

The term "picture element" as used herein may refer to an individual light-sensitive area or well of a pixel, or to an entire pixel (which may comprise multiple wells, see below). For every given projected spot, the detecting **120** of the first amount of light and the detecting **130** of the second amount of light occurs at the same one or the same group of the plurality of picture elements.

Without loss of generality, each of the picture elements may be a pixel comprising at least two charge storage wells **221, 222,** such that the detecting **120** of the first amount of light and the detecting **130** of the second amount of light can occur at the respective charge storage wells **221, 222** of the same pixel or pixel group. The third well may perform a variety of functions, provided that it is operated according to a timing scheme that takes into account the timing of the projector and/or the other wells.

Figure 2 schematically represents an embodiment of the system according to the present invention, in relation to an object **99** in the scenery of interest. The system **200** comprises a solid-state light source **210** for projecting a pattern of a sequence of spots, which may be repeated periodically, onto the object **99**. A detector **220** is arranged near the light source and configured to detect light reflected by the object.

The light beam bouncing off the object **99** is illustrated as an arrow in dashed lines, travelling from the light source **210** to the

object **99** and back to the detector **220**. It should be noted that this representation is strictly schematic, and not intended to be indicative of any actual relative distances or angles.

A synchronization means **230**, which may include a conventional clock circuit or oscillator, is configured to operate the solid-state light source **210** so as to project the pattern of spots onto the object during first predetermined time windows **10** and to operate the detector **220** so as to detect a first amount of light representing the light spot(s) reflected by the object **99** at substantially the same time. It further operates the detector **220** to detect a second amount of light representing the light spots reflected by the object **99**, during respective subsequent second predetermined time windows **20**. Appropriate processing means **240** are configured to calculate the distance to the object as a function of the first amount of reflected light and the second amount of reflected light.

Figure 3 (consisting of Figures 3a, 3b, and 3c) represents a timing diagram for light projection and detection in embodiments of the present invention. For clarity reasons, only a single pulse of the pulse sequence which is repeated periodically of Figure 3 is illustrated, which consists of a first time window **10** and a second time window **20**.

As can be seen in Figure 3a, during the first time window **10**, the solid-state light source **210** is in its "ON" state, emitting the pattern of light spots onto the scenery. During the second time window **20**, the solid-state light source **210** is in its "OFF" state.

The arrival of the reflected light at the detector **220** is delayed relative to the start of the projection by an amount of time that is proportional to the distance travelled (approximately 3.3 ns/m in free space) . Due to this delay, only a part of the reflected light will be detected at the first well **221** of the detector **220**, which is only activated during the first time window **10**. Thus, the charge accumulated in this first well during its period of

activation (the first time window **10**) consists of a part representing only the noise and the ambient light impinging on the pixel prior to the arrival of the reflected pulse, and a part representing the noise, the ambient light, and the leading edge of the reflected pulse.

The latter part of the reflected pulse will be detected at the second well **222** of the detector **220**, which is only activated during the second time window **20**, which preferably immediately follows the first time window **10**. Thus, the charge accumulated in this second well during its period of activation (the second time window **20**) consists of a part representing the noise, the ambient light, and the trailing edge of the reflected pulse, and a part representing only the noise and the ambient light impinging on the pixel after the arrival of the reflected pulse.

The greater the distance between the reflecting object **99** and the system **200**, the smaller the proportion of the pulse that will be detected in the first well **221** and the larger the proportion of the pulse that will be detected in the second well **222**.

If the leading edge of the reflected pulse arrives after the closing of the first well **221** (i.e., after the end of the first time window **10**), the proportion of the reflected pulse that can be detected in the second well **222** will decrease again with increasing time of flight delay.

The resulting amounts of charge **A**, **B** in each of the respective wells **221**, **222** for varying distances of the object **99** are shown in Figure 3b. To simplify the representation, the effect of the attenuation of light with distance, according to the inverse square law, has not been taken into account in the diagram. It is clear that for time of flight delays up to the combined duration of the first time window **10** and the second time window **20**, the time of flight delay can in principle unambiguously be derived from the values of **A** and **B**:

- For time of flight delays up to the duration of the first time window **10**, **B** is proportional to the distance of the object **99**. To easily arrive at a determination of the absolute distance, the normalized value **B/ (B+A)** may be used, removing any impact of non-perfect reflectivity of the detected object and of the inverse square law.
- For time of flight delays exceeding the duration of the first time window **10**, **A** consists of daylight and noise contributions only (not illustrated) , and **C—B** is substantially proportional (after correcting for the inverse square law) to the distance of the object **99**, where **C** is an offset value.

While Figures 3a and 3b illustrate the principle of the system according to the present invention in relation to a single pulse emitted in the time window **10**, it shall be understood that the illustrated pulse is part of a sequence of pulses as defined above. Figure 3c schematically illustrates exemplary timing characteristics of such a sequence. As illustrated, the illumination scheme **40** consists of a repeated emission of a sequence **30** of individual pulses **10**. The width of the individual pulses **10** is determined by the maximal operating range. The entire sequence may be repeated at a frequency of, for example, 60 Hz.

The inventors have found that in systems such as described herein, reflections of light by objects at a short distances are more likely to cause pixel saturation, because the attenuation of such a reflection will be much less than that of a reflection originating from a more distant object (due to the inverse-square law of light attenuation over distance) . As certain applications, such as automotive applications, require accurate system operation up to relatively long distances, a large photon span must be covered between the nearest distances of operation and the farthest distances of operation. With these constraints, pixel saturation at short range is a very real risk, in particular at the first well (which receives the bulk of the reflection at short range) . The inventors have found that for given total pixel space,

the saturation problem can be mitigated by using an asymmetric well arrangement, in which the photon capacity represented by the first well is increased, and the photon capacity represented by the second well is decreased. If the increase and decrease are balanced, an increase of the dynamic range can be obtained at no additional pixel surface cost.

The inventors have further found that to obtain a useful operating range (between the lowest detectable light level and the light level at which saturation occurs), the first charge storage should have a charge capacity that is at least 50% greater than the charge capacity of the second charge storage well. Preferably, the first charge storage should have a charge capacity that is at least 75% greater than the charge capacity of the second charge storage well, and most preferably the first charge storage should have a charge capacity that is at least 100% greater than the charge capacity of the second charge storage well.

An exemplary asymmetric dual-well pixel according to the present invention, including anti-blooming circuitry, is schematically presented in Figure 4. The charge storage wells 221, 222 (SN A, SN B) are connected to a photactive region (PH) by means of transfer gates (TG A, TG B), which are controlled to synchronize the active states of the two charge storage wells with the transmission of the projection pulses as described above.

Figure 5 schematically represents an embodiment of the pixel according to the present invention, showing a first way of obtaining the asymmetry of the wells. As shown in Figure 5, the first well 221 (the depletion zone on the A-signal side) has been made at least 50% larger than the second well 222 (the depletion zone on the B-signal side) during the semiconductor fabrication process .

Figure 6 schematically represents an embodiment of the pixel according to the present invention, showing a second way of obtaining the asymmetry of the wells. In this case, both

semiconductor wells **221, 222** are of identical side, but an additional capacitor is provided on the A-signal side to increase the effective capacity of the first well **221.**

Blooming is a phenomenon that happens when the charge in a pixel exceeds the saturation level of that specific pixel. Consequently, the charge starts to overflow and causes nuisance in adjacent pixels. This creates inaccurate data in the neighboring pixels, or in other wells of the same pixel. Preferably, the pixels of the system according to the present invention are provided with anti-blooming electronics, to bleed off the excess charge before it saturates the relevant well and spills over to the wells of adjacent pixels. In particular when the information from neighboring spots is used for the elimination of background light, it is of great importance to have an accurate estimation of the background light which is obtained independently (and without contamination from) neighboring pixels.

The pixel may further comprise circuitry allowing the pixel to switch between a charging mode and a discharging mode. In the charging mode, light impinging on said pixel causes the first charge storage well or the second charge storage well (according to the present stage of the illumination scheme) to increase a stored amount of charge. In the discharging mode, preferably activated after the charging mode for an equal amount of time, light impinging on said pixel causes said first charge storage well or said second charge storage well to decrease the stored amount of charge. This switching scheme allows an amount of charge corresponding to the background light to be removed from the charge storage wells.

Embodiments of the present invention may employ correlated double sampling to correct the samples for the thermal noise related to the capacity of the wells (also designated as "kTC noise") . To this end, the electronics of the pixel may be designed to carry out a differential measurement between the reset voltage (V_{reSet}) and the signal voltage (V_{signal}), for example by measuring V_{reSet} at

the beginning of the frame and measuring V_{signal} at the end of the frame. As an alternative to an electronic (in-pixel) implementation, correlated double sampling may also be implemented by digitally subtracting the read-out signals (V_{signal} - V_{reset}) in a processor.

To increase the amount of light that reaches the photosensitive elements (in particular diodes) in the pixel structure, embodiments of the present invention may use backside illumination; in that case, the pixel circuitry is behind the photosensitive layer, thus reducing the number of layers that must be traversed by the impinging photons to read the photosensitive elements .

In addition to being applicable in the system described above, the pixel and the pixel array according to the present invention may also be integrated with a triangulation-based system in accordance with WO 2015/004213 A1. If miniaturization is aimed for, the triangulation-based system will end up having a relatively small distance between its projector and its detector, thus leaving it with a reduced operating range. However, it is precisely at short range that the combination presents its benefit, because the triangulation-based system can cover the distances at which the time-of-flight based system cannot operate sufficiently accurately.

The entire ranging process may be repeated iteratively, preferably periodically, so as to monitor the distance to the detected object or objects over time. Thus, the result of this method can be used in processes that require information about the distance to detected objects on a continuous basis, such as advanced driver assistance systems, vehicles with an active suspension, or autonomous vehicles.

The entire ranging process may be repeated iteratively, so as to monitor the distance to the detected object or objects over time. Thus, the result of this method can be used in processes that

require information about the distance to detected objects on a continuous basis, such as detection and tracking of objects in the surroundings of a vehicle, advanced driver assistance systems, vehicles with an active suspension, autonomous driving or autonomous vehicles. An iteratively repeated range gating sequence is schematically represented in the timing diagram of Figure 7a, in which each frame corresponds of a sequence of pulses of the projector (P) (the timing of the pulses is indicated by the lowercase 'ρ'), which is synchronized to activations of the imager (I) (the accumulation of charges in the first well is indicated by the lowercase 'a', while the accumulation of charges in the second well is indicated by the lowercase 'b'). Without loss of generality, only two consecutive frames are illustrated.

Figure 7b represents a modified timing scheme, containing two additional time slots for every projection pulse. These additional time slots are used to discharge the respective wells at a rate proportional to the intensity of the light impinging on the pixel when no reflection of the projected light is received. As the light received in the absence of a pulse represents the background light, with only a tiny time offset relative to the point in time at which the pulse reflection is received, this scheme effectively removes the background light component from the charge accumulated in the first well and the second well, for each projector pulse.

In order to implement the above mentioned discharging phase, the pixel may comprise a capacitor for storing the charge, coupled to the photodiode by appropriate transfer gates. The accumulating phase then comprises transferring charges to a first side of the capacitor, and the decreasing comprises transferring charges to the second side of the capacitor.

The following timing diagrams illustrate how additional wells (e.g. the aforementioned third charge storage well and fourth charge storage well) may be used.

Figure 7c represents a modified timing scheme, containing one additional time slot for every projection pulse. This additional time slot is used to accumulate photocharges in a third well (the accumulation of charges in the third well is indicated by the lowercase 'c'). As the light received in the third well arrives in the absence of a pulse, it represents the background light, with only a tiny time offset relative to the point in time at which the pulse reflection is received. The charge accumulated in the third well may therefore be subtracted from the charges in the first well and the second well to effectively remove the background light component from the latter charges. The light received in the third well may also include reflections of projected spots arriving from highly reflective objects outside the range covered by the operation of the first well and the second well, and the accumulated charges may accordingly be used to detect such objects. The light received in the third well may also be used to generate a 2D image of the scenery, which may optionally be combined with the ranging information obtianed from the operation of the first well and the second well to create a 3D image.

Figure 7d represents a variant of the timing scheme of Figure 7c, in which the third well is activated during a number of time slots after the completion of the same number of projector pulses. As the light thus received in the third well arrives in the absence of a pulse, it represents the background light, with only a slightly larger time offset relative to the points in time at which the pulse reflection is received. The charge accumulated in the third well may therefore be subtracted from the charges in the first well and the second well to effectively remove the background light component from the latter charges. The charge accumulated in the third well in the separate time slots may also be used to generate a 2D image of the scenery, in which case the scenery may optionally be illuminated by a flash light.

Figure 7e represents yet another variant of the timing scheme of Figure 7c, in which the first well is activated in a separate frame, after the completion of a range-gating frame in which the

projector and the first and second well are active. As the light thus received in the first well arrives in the absence of a pulse, it represents the background light, with again a slightly larger time offset relative to the points in time at which the pulse reflection is received. The charge accumulated in the first well in the separate frame may therefore be subtracted from the charges previously accumulated in the first well and the second well to effectively remove the background light component from the latter charges. The charge accumulated in the first well in the separate frame may also be used to generate a 2D image of the scenery, in which case the scenery may optionally be illuminated by a flash light .

The combination of the large desired operational range (in the order of 200 m) and the high desired accuracy (correctly detect as few as 1000 photons at the furthest point) results in a huge span between the largest number of photons that may be received in one well in one frame (in the case of reflections at short range) , and the lowest number that may be received in one well in one frame.

Figure *1f* represents a modified timing scheme, which differs from the scheme of Figure 7a in that the duration of a single time slot varies from one slot to the next. In this way, the detection threshold and the saturation point for different frames will occur at different distances, and the information obtained from a number of consecutive frames may be combined to obtain accurate distance measurements for both nearby objects and far-away objects.

Figure 7g schematically illustrates how the individual frames in the sequence of Figure 3c, which may fail to cover the entire targeted range of distances $[z_{min}, z_{max}]$ as a result of the constraints imposed by N_{max} (maximal number of electrons that can be stored without saturating the pixel) and N_{min} (minimum number of pixels required for accurate read-out) , can be broken down into sequences with different timing parameters, each covering a portion of the targeted range $[z_{min}(i), z_{max}(i)]$ that can more

easily be covered within the same constraints on the number of photons .

With reference to the symbols introduced above and used in Figure 7g, the corresponding electron amounts $n_{min\,(i)}$ and $n_{max\,(i)}$ of the subranges are defined by:

- The maximum allowable number of electrons (using "FPC" for the full pixel capacity, which corresponds to full well capacity in case there are no additional capacities) :

  $n_{max} = N_{min} \times \left(\frac{z(i)}{z(i+1)}\right) \leq FPC$, with $z_{(0)} = Z_{max}$

- The minimum required accuracy level : $n_{min} = N_{min}$
- $Z_{max\,(i)} = Z_{min\,(i-1)}$

Additionally, the pulse characteristics can be determined as follows :

- the pulsewidth $\tau(i) = \frac{2z_{max}(i)}{c}$
- the total "on" time is reduced proportionally to $\frac{N_{max}}{N_{min}}$ to respect the limits imposed by the full pixel capacity and the accuracy level.

The above principles may be further clarified by the following non-limiting numerical example.

A Lambertian reflecting surface with 10% reflectivity at a distance of 150m must provide 1000 electrons to obtain an accuracy of 1,6%. At the same distance, a 100% reflecting surface will generate 10000 electrons. With a full well capacity of 200000 electrons, the following multi-frame solution is proposed:

	Sub-range	Pulse Width	Total "on" time
Frame 1	150m - 33m	1 µs	1 ms
Frame 2	7.4m - 33m	22 ns	50 µs
Frame 3	1.65m - 7.4m	4.9 ns	2.5 µs
Frame 4	0.37m - 1.65m	1.1 ns	0.125 µs

It should be noted that for robustness reasons, it may be advantageous to provide an overlap in the subranges .

For assuring the same 3D resolution, it may be advantageous to use a faster camera: e.g., a camera operating at 180Hz with 3-frame interleaving gives the same data speed as a 60Hz with single frame operation .

Depending on the mode in which a system according to the present invention is used (as exemplified in Figures 7a-7g) , the duty cycle will vary. It can easily be seen that when some frames are used for capturing out-of-range reflections or acquiring a 2D image, a smaller fraction of time is available for the actual ranging. It is an advantage of the use of three-well or four-well pixel according to the present invention that several functions can be performed simultaneously.

Blooming is a phenomenon that happens when the charge in a pixel exceeds the saturation level of that specific pixel (as in the case of short-range reflections or reflections from highly reflective surfaces such as traffic signs or license plates) . Consequently, the charge starts to overflow and causes nuisance in adjacent pixels. This creates inaccurate data in the neighboring pixels. Preferably, the pixels of the system according to the present invention are provided with anti-blooming electronics, which may in particular include a fourth well, to bleed off the excess charge before it saturates the relevant well and spills over to the wells of adjacent pixels. In particular when the information from neighboring spots is used for the elimination of background light, it is of great importance to have an accurate estimation of the background light which is obtained independently (and without contamination from) neighboring pixels. Likewise, when the pixels that do not receive spot reflections are used to simultaneously generate a regular 2D image, it is highly desirable that pixels adjacent to pixels receiving a spot reflection are not affected by charge spills from the latter pixels.

In order for all elements of the system as described to operate optimally, the system has to be thermally stable. Thermal stability avoids, among other things, undesired wavelength shifts of the optical elements (thermal drift), which would otherwise impair the proper functioning of the optical filters and other elements of the optical chain. Embodiments of the system according to the present invention achieves thermal stability by their design, or by active regulation by means of a temperature control loop with a PID-type controller.

WO 2015/004213 A1 discloses various techniques to minimize the amount of ambient light that reaches the pixels during the detection intervals, thus improving the accuracy of the detection of the patterned laser spots. While these techniques have not been disclosed in the context of a LIDAR system, the inventors of the present invention have found that several such techniques yield excellent results when combined with embodiments of the present invention. This is particularly true for the use of narrow bandpass filters at the detector, and the use of adequate optical arrangements to ensure nearly perpendicular incidence of the reflected light onto the filters. The details of these arrangements as they appear in WO 2015/004213 A1 are hereby incorporated by reference. Further features and details are provided hereinafter.

European patent application publication nos. EP 3045935 B1 and EP 3045936 B1, both in the name of the present applicant, disclose optical arrangements that may be used in conjunction with the system disclosed in the present application to further minimize the amount of ambient light that reaches the pixels during the detection intervals. The details of these arrangements as they appear in EP 3045935 B1 and EP 3045936 B1 are hereby incorporated by reference. Accordingly, a pixel according to the present invention may be provided with a microlens in order to guide the impinging light, after optional filtration, to the photosensitive region.

While these various techniques may be applied to embodiments of the present invention to minimize the amount of ambient light that reaches the pixels during the detection intervals, a certain amount of ambient light cannot be avoided. In a multi-pixel system, only some of the pixels will be illuminated by reflected spots, while others will be illuminated by residual ambient light only. The signal levels of the latter group of pixels can be used to estimate the contribution of the ambient light to the signals in the pixels of interest, and to subtract that contribution accordingly .

In some embodiments, the detector may be a high dynamic range detector, i.e. a detector having a dynamic range of at least 90 dB, preferably at least 120 dB. The presence of a high dynamic range sensor, i.e. a sensor capable of acquiring a large amount of photons without saturation while maintaining sufficient discrimination of intensity levels in the darkest part of the scene, is an advantage of the use of such a sensor; it allows for a sensor that has a very long range and yet remains capable of detection objects at short distance (where the reflected light is relatively intense) without undergoing saturation. The inventors have found that the use of a high dynamic range sensor not based on tone mapping is more advantageous than the use of a sensor that applies tone mapping. In tone mapping, the sensor linear range is compressed towards the higher resolution. In literature, several compression methods are documented, such as logarithmic compression or multilinear compression. However, this non-linear compression necessitates relinearization of the signals before performing logical or arithmetic operations on the captured scene to extract the relief information. The solution according to the invention therefore increases detection accuracy without increasing the computational requirements. It is a further advantage of some embodiments to use a fully linear high dynamic range sensor. A pixel architecture and an optical detector that are capable of providing the desired dynamic range characteristics are disclosed in US patent application publication no. US

2014/353472 A1, in particular paragraphs 65-73 and 88, the content of which is incorporated by reference for the purpose of allowing the skilled person to practice this aspect of the present invention .

Embodiments of the present invention use a high dynamic range pixel. This can be obtained by a sizeable full-well capacity of the charge reservoirs or by designs limiting the electronic noise per pixel or by usage of CCD gates that do not add noise at charge transfer, or through a design with a large detection quantum efficiency (DQE) (e.g., in the range of 50% for front illumination or 90% in case of back illumination, also known as back thinning) , or by a special design, or by any combination of the listed improvements. Furthermore, the dynamic range can be further enlarged by adding an overflow capacity to the pixel in overlay at its front side (this implementation requires back thinning) . Preferably, the pixel design implements an anti-blooming mechanism.

A system according to the invention may include an implementation of steps of the methods described above in dedicated hardware (e.g., ASIC), configurable hardware (e.g., FPGA) , programmable components (e.g., a DSP or general purpose processor with appropriate software), or any combination thereof. The same component (s) may also include other functions. The present invention also pertains to a computer program product comprising code means implementing the steps of the methods described above, which product may be provided on a computer-readable medium such as an optical, magnetic, or solid-state carrier.

The present invention also pertains to a vehicle comprising the system described above.

Embodiments of the present invention may be used advantageously in a wide variety of applications, including without limitation automotive applications, industrial applications, gaming applications, and the like, and this both indoor and outdoor, at

short or long range. In some applications, different sensors according to embodiments of the present invention may be combined (e.g., daisy-chained) to produce panoramic coverage, preferably over a full circle (360° field of view).

It should be noted that the method, the pixel, and the pixel array according to the present invention may also be used in triangulation-based systems such as the system of WO 2015/004213 A1, and in existing LIDAR systems, to improve the quality of the measurements in the presence of ambient light.

While the invention has been described hereinabove with reference to separate embodiments, this was done for clarifying purposes only. The skilled person will appreciate that features described in connection with one embodiment, can also be applied to other embodiments, with the same technical effects and advantages. Furthermore, the scope of the invention is not limited to these embodiments, but is defined by the accompanying claims.

Claims

1. A pixel for use in a system for determining a distance to an object by range gating,
said pixel comprising:
a first charge storage well (221) and a second charge storage well (222) for accumulating electrical charges representative of amounts of light reflected by said object and impinging on said pixel during respective sets of exposure intervals, and a third charge storage well (223);
wherein said first charge storage well (221) has a charge capacity that is at least 50% greater than a charge capacity of said second charge storage well (222); and
wherein said third charge storage well (223) has a smaller charge storage capacity than said first charge storage well (221) and said second charge storage well (222).

2. The pixel according to claim 1, further comprising circuitry allowing said pixel to switch between:
- a charging mode, in which light impinging on said pixel causes said first charge storage well (221) or said second charge storage well (222) to increase a stored amount of charge, and
- a discharging mode, in which light impinging on said pixel causes said first charge storage well (221) or said second charge storage well (222) to decrease a stored amount of charge.

3. The pixel according to any of the preceding claims, further comprising circuitry allowing photocharges that are generated when an active one of said first charge storage well (221) and said second charge storage well (222) is filled to capacity, to be to deviated to a charge sink without entering a storage well of an adjacent pixel.

4. The pixel according to any of the preceding claims, further comprising a fourth charge storage well (224).

5. An imaging array comprising a plurality of pixels according to any of the preceding claims.

6. A system for determining a distance to an object comprising:

- a solid-state light source arranged for projecting a pattern of spots, preferably discrete spots, of light towards the object in a sequence of pulses, preferably a periodically repeated sequence of pulses;
- a detector comprising an imaging array according to claim 5, the detector being configured for detecting light representing the pattern of spots as reflected by the object in synchronization with said sequence of pulses; and
- processing means configured to calculate the distance to the object as a function of exposure values generated by said pixels in response to said detected light;

wherein the pixels of the imaging array are configured to generate said exposure values by accumulating, for all pulses of said sequence, a first amount of electrical charge representative of a first amount of light reflected by said object during a first predetermined time window and a second electrical charge representative of a second amount of light reflected by said object during a second predetermined time window, said second predetermined time window occurring after said first predetermined time window, and

wherein the detecting of the first amount of light and the detecting of said second amount of light occurs at said first charge storage well (221) and at said second charge storage well (222), respectively.

7. The system according to claim 6, further configured to perform the projecting and the detecting for at least two consecutive sequences of pulses, each of the sequences being operated with a different duration of the first predetermined time window and the second predetermined time window.

8. The system according to claim 6 or claim 7, wherein the imaging array is further adapted to perform 2D video image acquisition.

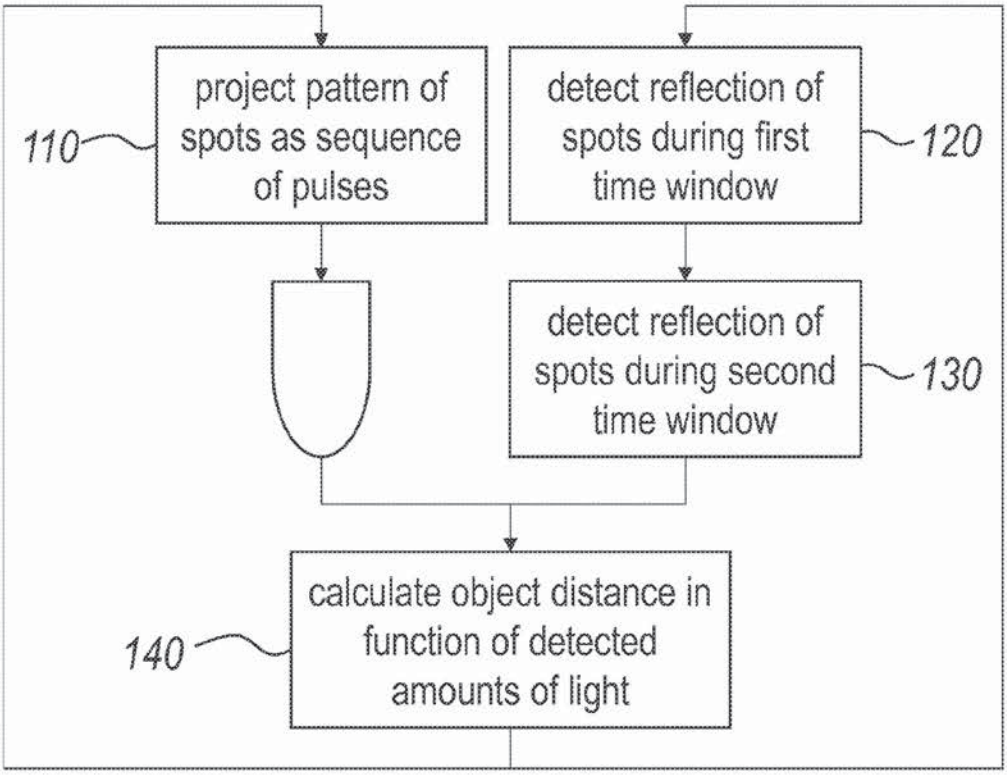

project pattern of spots as sequence of pulses
110
detect reflection of spots during first time window
120
detect reflection of spots during second time window
130
calculate object distance in function of detected amounts of light
140

Fig. 1

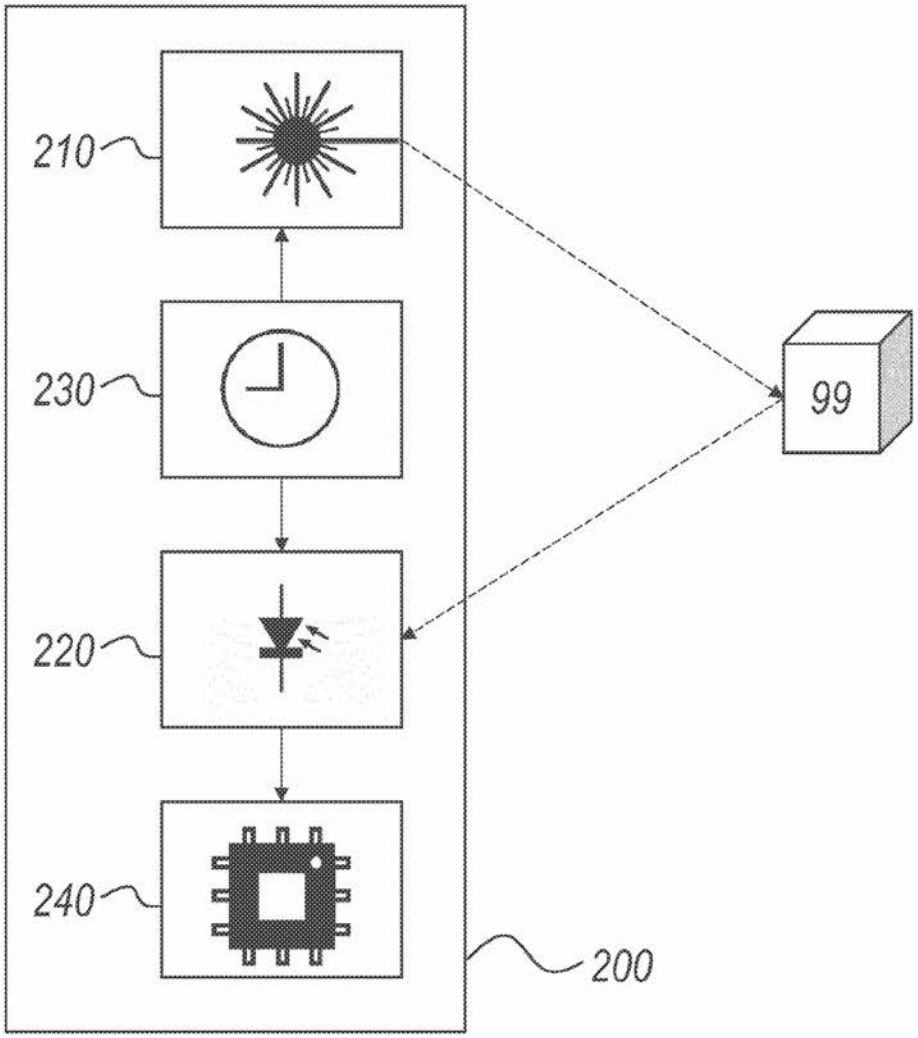


Fig. 2

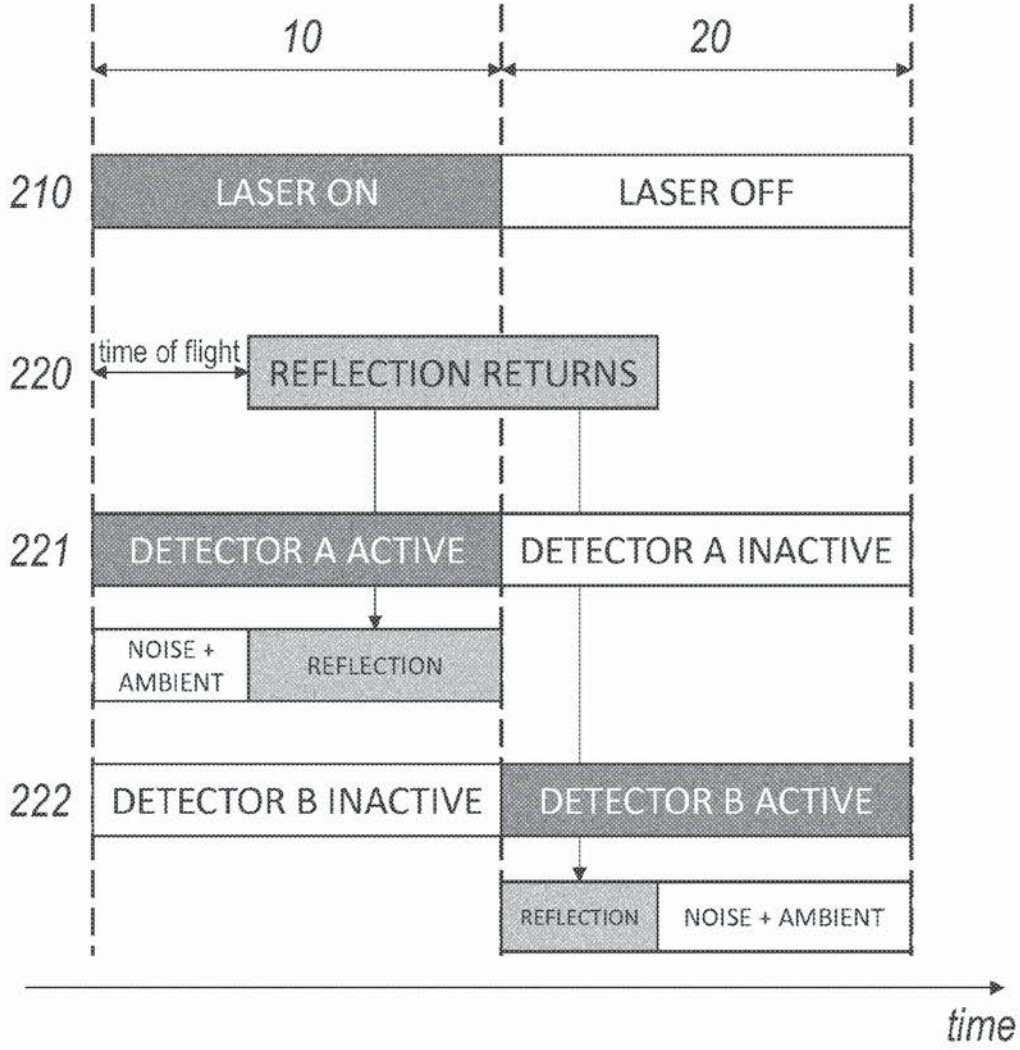

10
20
210
LASER ON
LASER OFF
220
time of flight
REFLECTION RETURNS
221
DETECTOR A ACTIVE
DETECTOR A INACTIVE
NOISE + AMBIENT
REFLECTION
222
DETECTOR B INACTIVE
DETECTOR B ACTIVE
REFLECTION
NOISE + AMBIENT
time

Fig. 3a

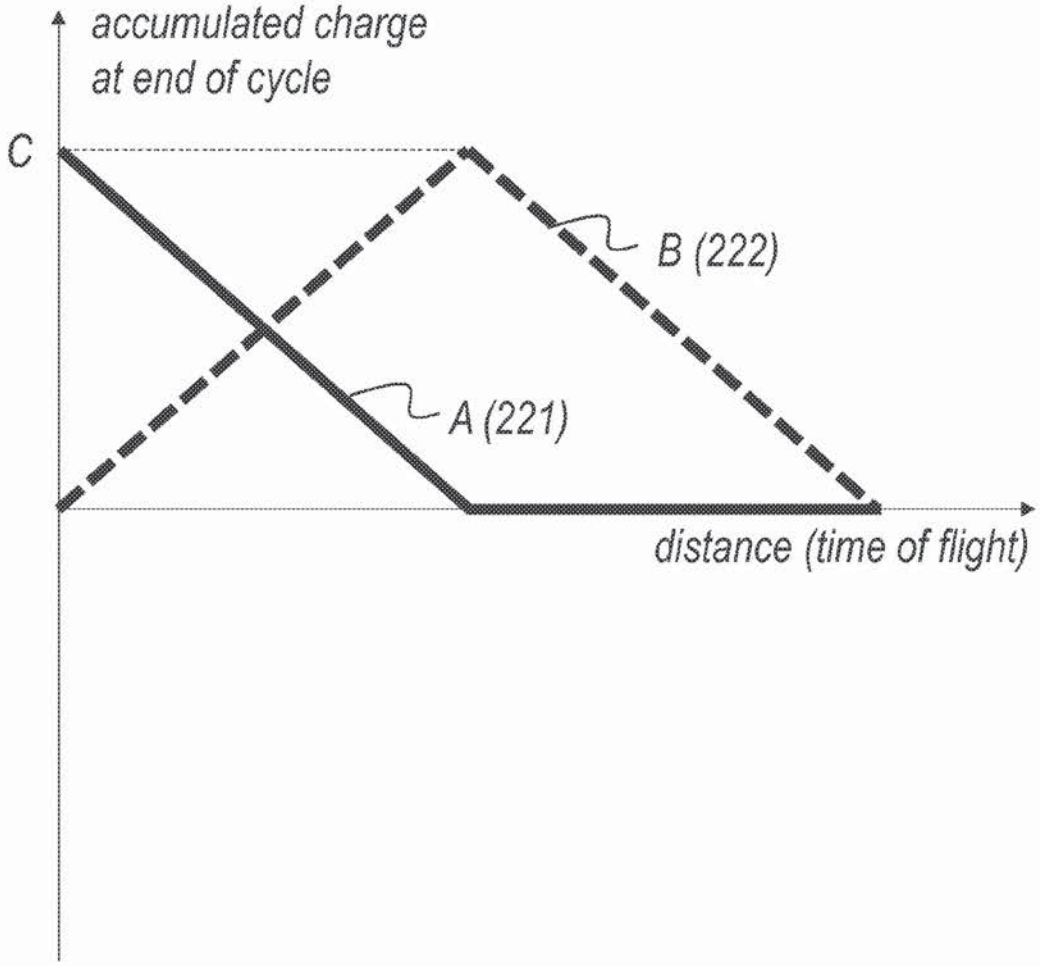

accumulated charge
at end of cycle
C
B (222)
A (221)
distance (time of flight)

Fig. 3b

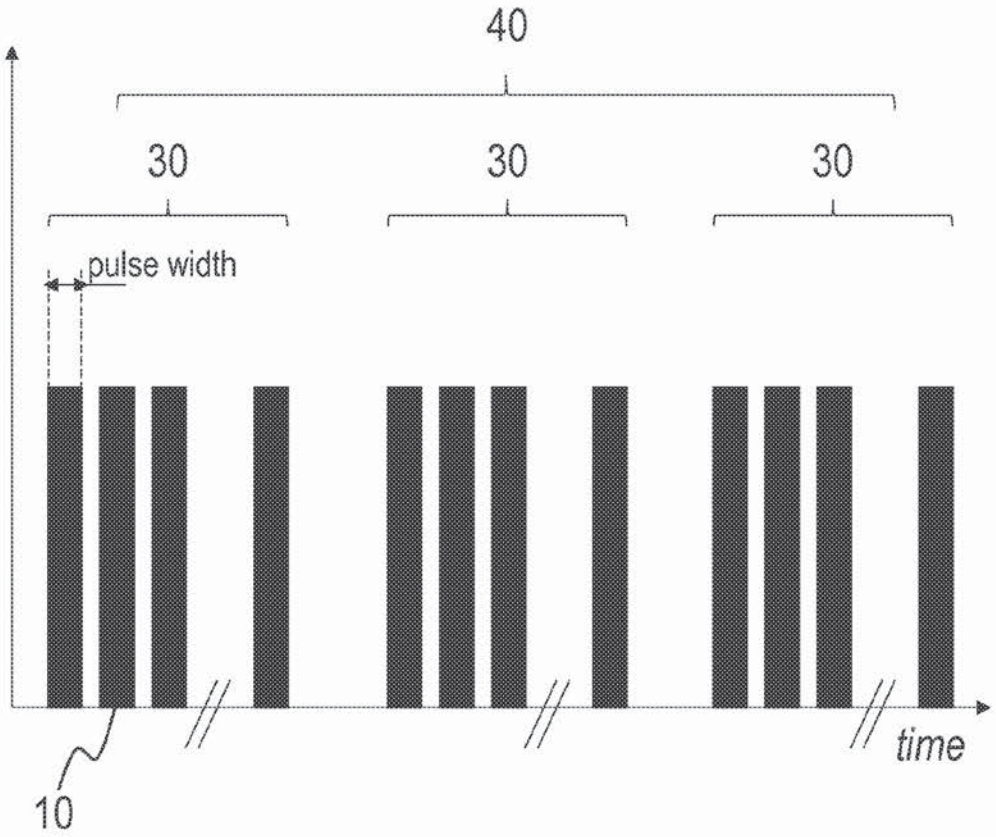


Fig. 3c

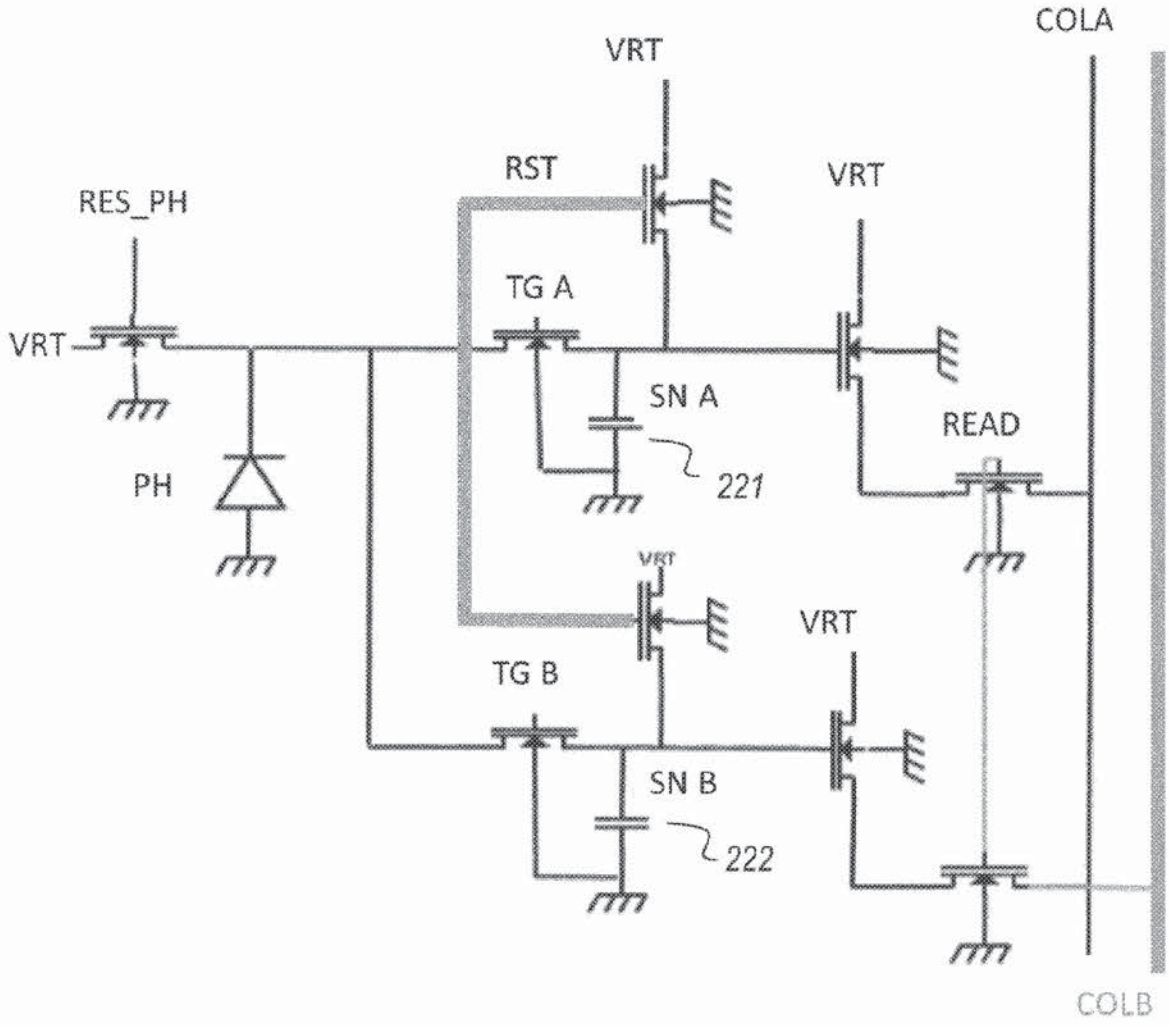

COLA
VRT
RST
VRT
RES_PH
TG A
VRT
SN A
READ
221
PH
VRT
VRT
TG B
SN B
222
COLB

Fig. 4

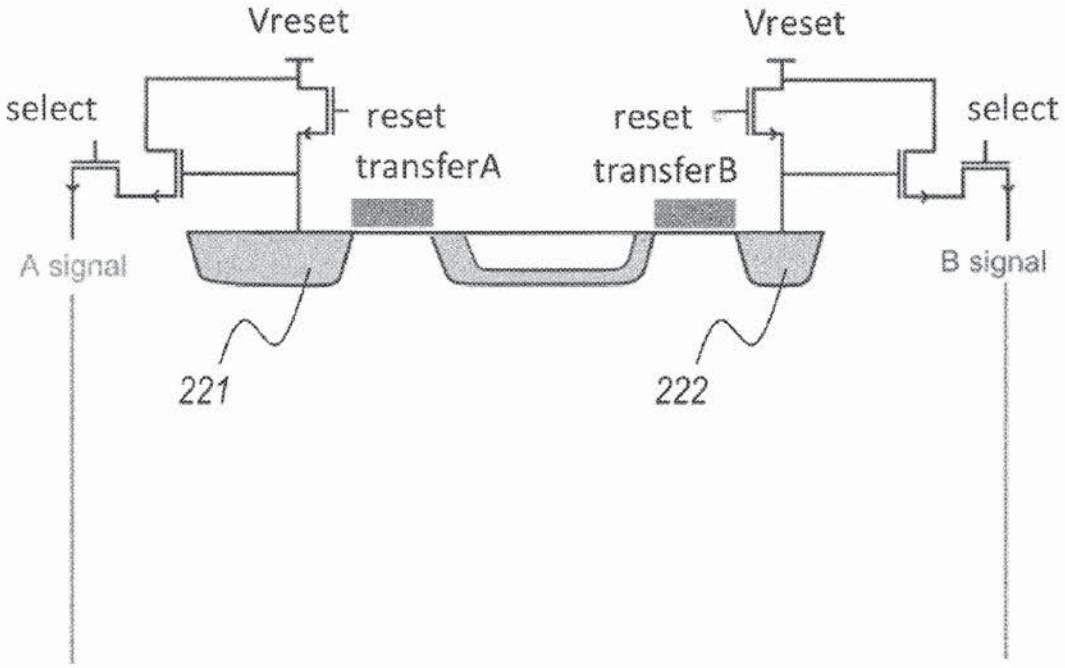

Vreset
Vreset
select
reset
transferA
reset
transferB
select
A signal
B signal
221
222

Fig. 5

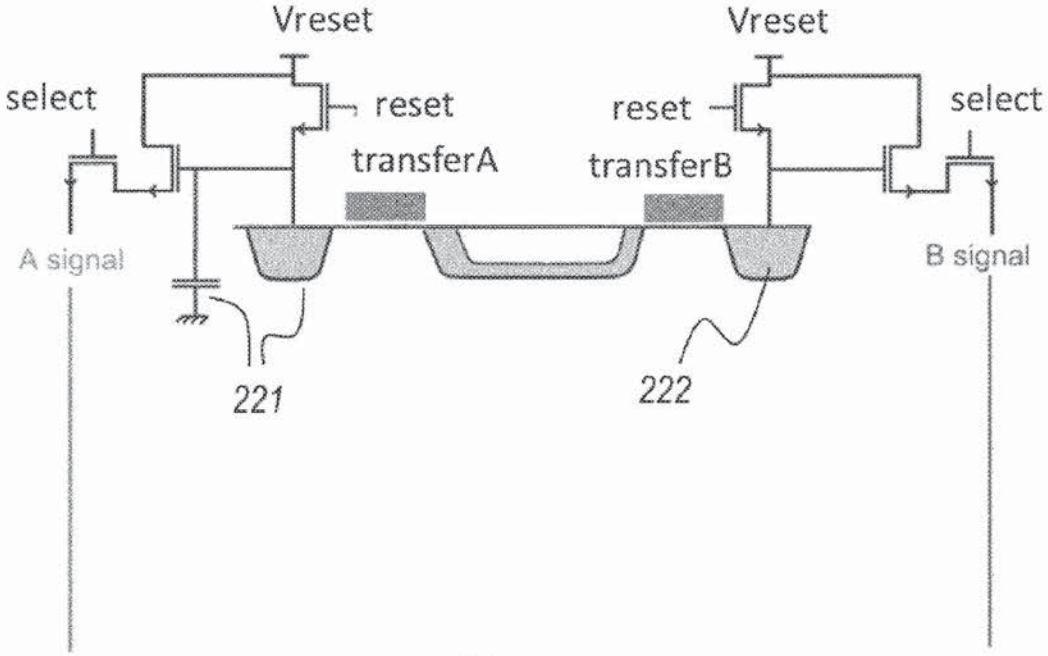

Vreset
Vreset
select
reset
transferA
reset
transferB
select
A signal
B signal
221
222

Fig. 6

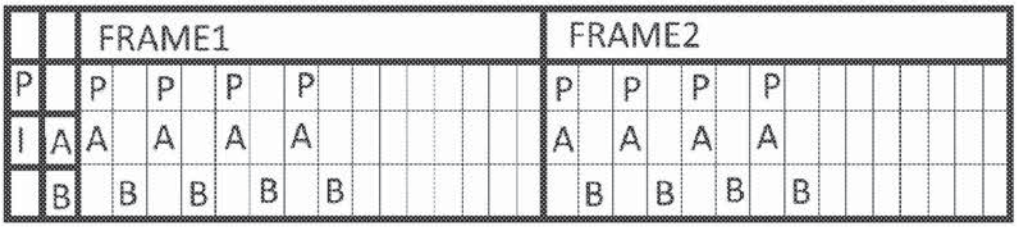


Fig. 7a

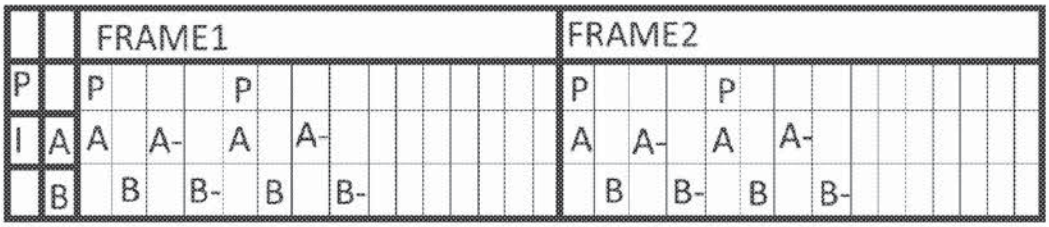


Fig. 7b

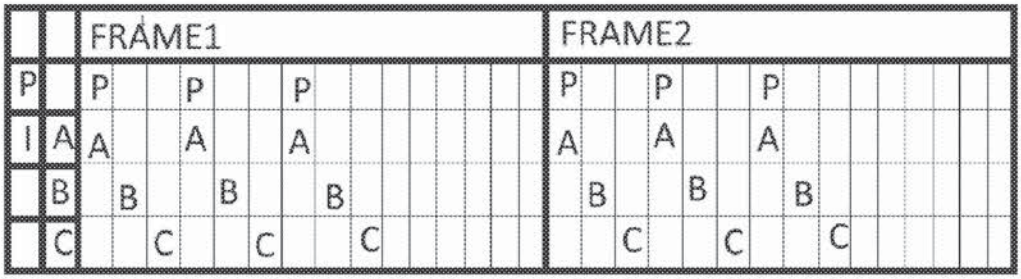


Fig. 7c

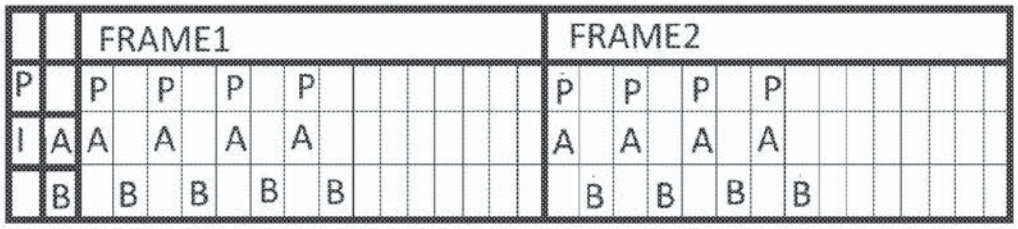


Fig. 7d

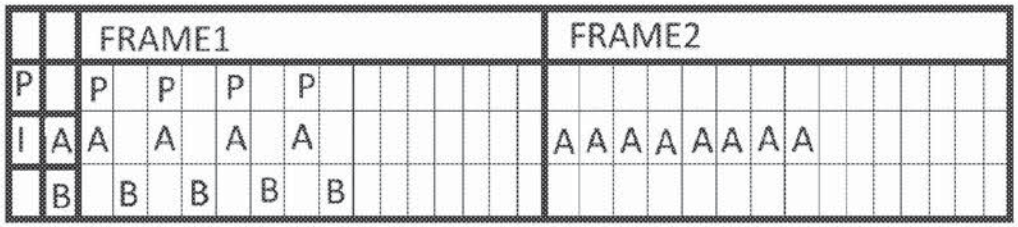


Fig. 7e

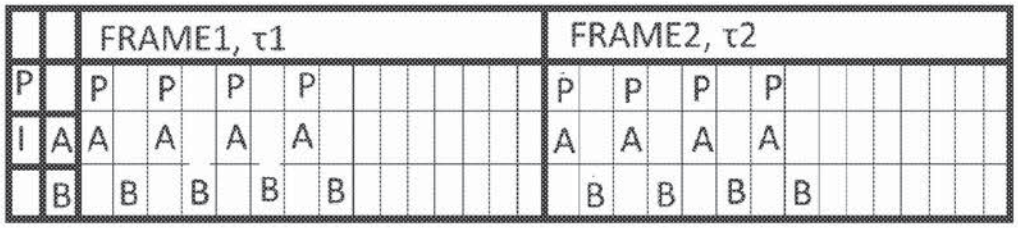


Fig. 7f

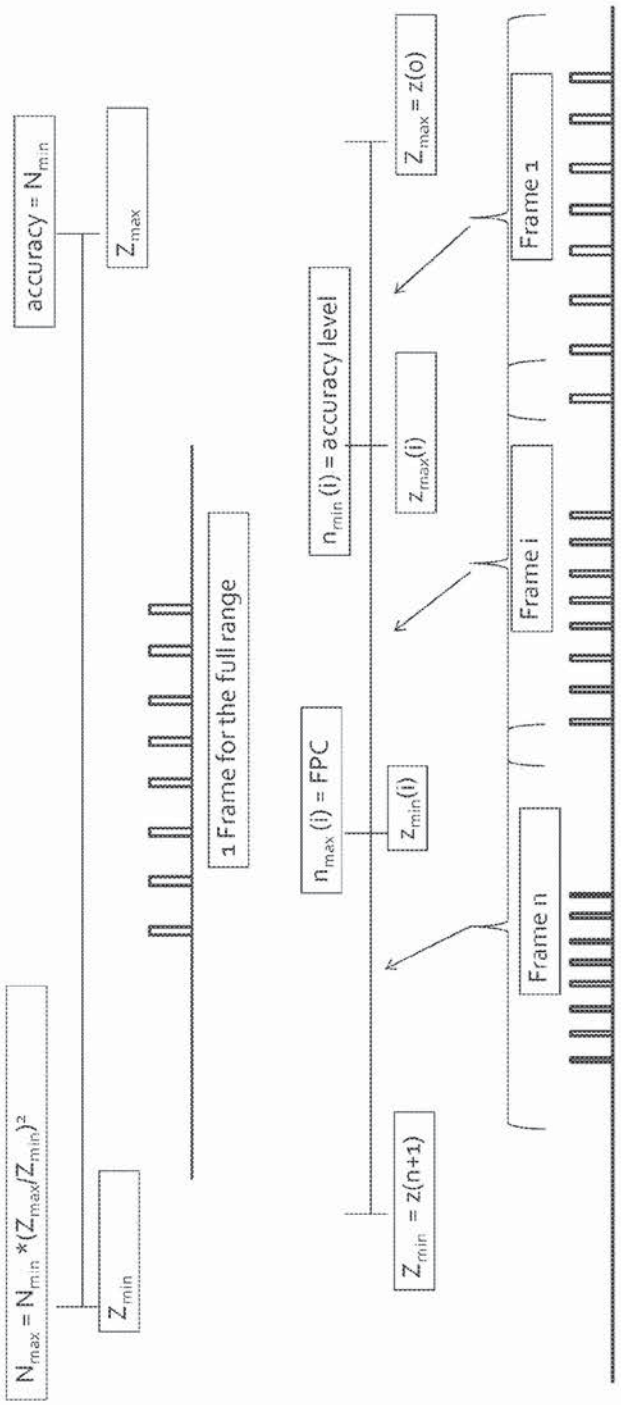

accuracy = N_{min}
Z_{max}
$N_{max} = N_{min} * (Z_{max}/Z_{min})^2$
Z_{min}
1 Frame for the full range
n_{max} (i) = FPC
n_{min} (i) = accuracy level
Z_{min}(i)
Z_{max}(i)
Z_{min} = z(n+1)
Z_{max} = z(0)
Frame n
Frame i
Frame 1

Fig. 7g

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/060391

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S17/10 G01S17/89 G01S7/486
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01S G01B H04N H01L

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal , COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/041077 A1 (FOSSUM ERIC R [US]) 4 March 2004 (2004-03-04)	1-5
A	abstract; figures 18-21 paragraphs [0015] , [0059] - [0061] , [0077] - [0080] , [0091] , [0092]	6-8
A	US 2015/253429 A1 (DORRINGTON ADRIAN ANDREW [NZ] ET AL) 10 September 2015 (2015-09-10) paragraphs [0013] , [0030] , [0089] , [0118] ; figure 5c	6-8
A	US 2015/144790 A1 (VELICHKO SERGEY [US] ET AL) 28 May 2015 (2015-05-28) paragraphs [0014] - [0016] , [0019] , [0031] - [0040] ; figures 5,6	1-8

-/- .

X Further documents are listed in the continuation of Box C.

X See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" documentwhich may throw doubts on priority claim(s) orwhich is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 July 2018	06/08/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Grubl , Alexander

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/060391

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 3 045 935 A1 (XENOMATIX BVBA [BE]) 20 July 2016 (2016-07-20) cited in the application abstract -----	6

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2018/060391

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2004041077 A1	04-03-2004	US 2004041077 A1	04-03-2004
		US 2005168608 A1	04-08-2005
		US 2009021627 A1	22-01-2009
US 2015253429 A1	10-09-2015	CN 106662650 A	10-05-2017
		EP 3114503 A2	11-01-2017
		US 2015253429 A1	10-09-2015
		WO 2015133910 A2	11-09-2015
US 2015144790 A1	28-05-2015	NONE	
EP 3045935 A1	20-07-2016	NONE	

Form PCT/ISA/210 (patent family annex) (April 2005)

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
05 July 2018 (05.07.2018)

W!P O | PCT

(10) International Publication Number
WO 2018/122415 A1

(51) International Patent Classification:
G01S 17/10 (2006.01) *G01S 17/93* (2006.01)
G01S 17/89 (2006.01)

(21) International Application Number:
PCT/EP2018/050080

(22) International Filing Date:
02 January 2018 (02.01.2018)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
16207630.1 30 December 2016 (30.12.2016) EP

(71) Applicant: **XENOMATIX NV** [BE/BE]; Esperantolaan 4, B-3001 Leuven (BE).

(72) Inventor: **GEUENS, Filip**; Benedenstraat 20, B-3220 Holsbeek (BE).

(74) Agent: **IPLODGE BVBA**; Technologielaan 9, B-3001 Heverlee (BE).

(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).

Declarations under Rule 4.17:
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

(54) Title: SYSTEM FOR CHARACTERIZING SURROUNDINGS OF A VEHICLE

(57) Abstract: The invention pertains to a system for characterizing surroundings of a vehicle, the system comprising: projection means (210) arranged for projecting a pattern of laser light towards said surroundings in a sequence of pulses; a detector (220) comprising a plurality of pixels, said detector (220) being configured for detecting light representing said pattern of laser light as reflected by said surroundings in synchronization with said sequence of pulses; and processing means (240) configured to calculate distances to objects (99) in said surroundings as a function of exposure values generated by said pixels in response to said detected light; wherein said detector (220) is further configured for detecting light forming a two-dimensional image of said surroundings at points in time that do not coincide with said sequence of pulses or at pixels that do not receive said light representing said pattern of laser light as reflected by said surroundings.

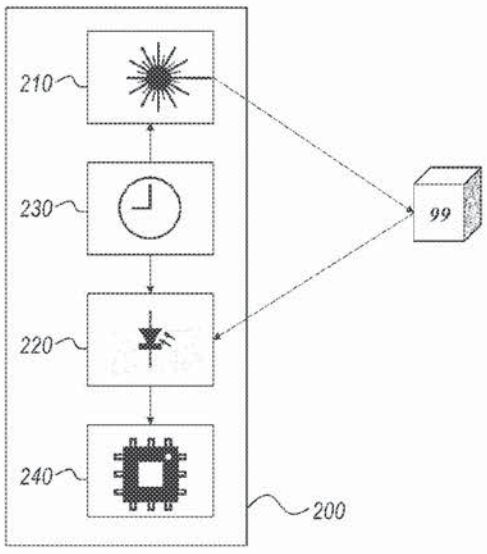


Fig. 1

WO 2018/122415 A1

System for characterizing surroundings of a vehicle

Field of the Invention

The present invention pertains to the field of systems for determining a distance to an object, in particular to sensing systems to be used for the characterization of a scene or a part thereof, as may be used to detect obstacles in the vicinity of a vehicle .

Background

In the field of remote sensing technology, in particular with regard to the generation of high-resolution maps of a scenery which can be used in control and navigation applications including automotive and industrial applications, gaming applications, and mapping applications, it is known to use triangulation-based and time-of-flight based sensing to determine the distance of objects from a sensor.

A high-accuracy medium-range surround sensing system for vehicles that makes use of triangulation, is known from international patent application publication WO 2015/004213 A1 in the name of the present applicant. In that patent application, the localization of objects is based on the projection of pulsed radiation spots and the analysis of the displacement of detected spots with reference to predetermined reference spot positions. More in particular, the system of the cited patent application uses triangulation. However, the accuracy that can be achieved correlates with the triangulation base, which limits the miniaturization that can be achieved.

Time-of-flight based techniques include the use of RF modulated sources, range gated imagers, and direct time-of-flight (DToF) imagers. For the use of RF modulated sources and range gated imagers, it is necessary to illuminate the entire scene of interest with a modulated or pulsed source. Direct time-of-flight

systems, such as most LIDARs, mechanically scan the area of interest with a pulsed beam, the reflection of which is sensed with a pulse detector. The optical power emitted by present semiconductor lasers cannot meet the power requirements necessary for operations in the known LIDAR systems to be of practical use in automotive applications (e.g. for ranges up to 250 m). Unpublished European patent application no. EP 15 191 288.8, in the name of the present applicant, describes a system for determining a distance to an object that overcomes such limitations. It comprises: a solid-state light source arranged for projecting a pattern of discrete spots of laser light towards the object in a sequence of pulses; a detector comprising a plurality of pixels, the detector being configured for detecting light representing the pattern of discrete spots as reflected by the object in synchronization with said sequence of pulses; and processing means configured to calculate the distance to the object as a function of exposure values generated by said pixels in response to said detected light. The pixels are configured to generate said exposure values by accumulating, for each pulse of said sequence, a first amount of electrical charge representative of a first amount of light reflected by said object during a first predetermined time window and a second electrical charge representative of a second amount of light reflected by said object during a second predetermined time window, said second predetermined time window occurring after said first predetermined time window.

As remote sensing technology is increasingly being relied on to provide vehicle-safety features, advanced driver assistance systems (ADAS), and even autonomous (or "self-driving") cars, there is a need for a system that more accurately characterize the surroundings of the vehicle in which the system is mounted.

Summary of the Invention

According to an aspect of the present invention, there is provided a system for characterizing surroundings of a vehicle, the system comprising:

- a projection means arranged for projecting a pattern of laser light towards said surroundings in a sequence of pulses, said pattern of laser light comprising a pattern of discrete spots;
- a detector comprising a plurality of pixels, said detector being configured for detecting light representing said pattern of laser light as reflected by said surroundings in synchronization with said sequence of pulses; and
- processing means configured to calculate distances to objects in said surroundings as a function of exposure values generated by said pixels in response to said detected light;

wherein said detector is further configured for detecting light forming a two-dimensional image of said surroundings at points in time that do not coincide with said sequence of pulses or at pixels that do not receive said light representing said pattern of laser light as reflected by said surroundings.

It is an advantage of the invention that the characterization of the surroundings can be improved by combining 2D information and 3D information obtained from the same sensor at interleaved points in time. The 3D information is obtained from the system when used as a range sensor, by capturing the reflected light patterns in synchronization with their projection; and the 2D information is obtained from the system when used as a digital camera between the range sensing pulses.

The projection means preferably comprises a solid-state laser; it could in particular be a VCSEL array or a solid-state laser provided with an adequate grating. The pattern of laser light is preferably a pattern of spots, in particular discrete spots. The sequence of pulses may be periodically repeated, to allow for a continuous updating of the characterization of the surroundings.

In an embodiment of the system according to the present invention, the pixels are configured to generate said exposure values by accumulating, for all of the pulses of said sequence, a first amount of electrical charge representative of a first amount of light reflected by said objects during a first predetermined time window and a second electrical charge representative of a second amount of light reflected by said objects during a second predetermined time window, said second predetermined time window occurring after said first predetermined time window.

It is an advantage of this embodiment that it uses range-gated LIDAR techniques to obtain accurate distance information in a small form factor.

In an embodiment of the system according to the present invention, said processing means are adapted to determine said distances by determining a displacement of features of said detected light representing said pattern of laser light as reflected by said surroundings with reference to predetermined feature positions.

In this embodiment, the respective exposure values of the different pixels of the detector are analyzed to determine in which pixels reflections of the projected pattern (e.g. spots) are detectable, and in which they are not. In this manner, the displacement of parts of the reflected pattern relative to predetermined positions (e.g. spot positions) can be determined, which yields information about the distance of the objects that have reflected the respective parts of the projected pattern. It is an advantage of this embodiment that it uses familiar triangulation-based techniques to obtain accurate distance information .

In an embodiment, the system according to the present invention comprises illumination means configured to project a bundle of light onto said surroundings at said points in time that do not coincide with said sequence of pulses.

The bundle of light is intended for a homogeneous illumination of the relevant part of the surroundings, preferably coinciding with the field of view of the detector, so, unlike the projected pattern used for ranging, it must be substantially homogeneous. It is an advantage of this embodiment, that the scenery to be captured in the 2D image can be adequately lit, even when the ambient light conditions are unfavorable (e.g., at night) .

In a particular embodiment, the projection means and the illumination means share a common light source.

It is an advantage of this particular embodiment, that the system can be kept compact by avoiding the need for multiple light sources .

In a more particular embodiment, the common light source comprises a VCSEL array, and the illumination means further comprises an actively steered diffuser, configured to be activated at said points in time that do not coincide with said sequence of pulses, so as to diffuse light originating from the VCSEL array to form the bundle.

It is an advantage of this more particular embodiment, that a VCSEL array, which is well suited for projection of structured light, can also be used to provide the illumination required for 2D image capturing.

In an embodiment of the system according to the present invention, the plurality of pixels of the detector are provided with a time-dependent filter allowing light in different wavelength bands to reach the plurality of pixels at different ones of said points in time .

It is an advantage of this embodiment that an RGB image can be produced by combining three different 2D exposures that are slightly offset in time. An RGB image yields more accurate

automated feature recognition and is generally more suited for visual reproduction to a human user than a monochrome image.

In an embodiment of the system according to the present invention, the different pixels of the plurality of pixels of the detector are provided with different filters allowing light in different wavelength bands to reach the different pixels at said points in time.

It is an advantage of this embodiment that an RGB image can be produced by combining exposure values that are obtained at pixels that are slightly offset in space. An RGB image yields more accurate automated feature recognition and is generally more suited for visual reproduction to a human user than a monochrome image.

According to an aspect of the present invention, there is provided a vehicle comprising the system according to any of the preceding claims arranged so as to characterize an area surrounding said vehicle.

The present invention is well suited for use in vehicles, in particular road vehicles such as automobiles. The system may thus advantageously contribute to vehicle-safety features, advanced driver assistance systems (ADAS), and even autonomous (or "self-driving") cars. As sensors in automotive applications are competing for space, it is an additional advantage of the present invention that it combines multiple functions in the same sensor, thus providing 2D and 3D sensor fusion without requiring an additional external 2D sensor.

Brief Description of the Figures

These and other aspects and advantages of the present invention will now be described in more detail with reference to the accompanying drawings, in which:

Figure 1 schematically illustrates an embodiment of the system according to the present invention;

Figures 2-4 illustrate the operating principles of a LIDAR-based embodiment of the system according to the present invention;

Figure 5 presents several timing diagrams that can be used in embodiments of the present invention;

Figure 6 schematically illustrate a pixel arrangement for use in an embodiment of the system according to the present invention; and

Figure 7 schematically illustrate timing diagrams that can be used in embodiments of the present invention.

Detailed Description of Embodiments

Figure 1 schematically illustrates an embodiment of the system according to the present invention.

The system is intended and adapted for characterizing surroundings of a vehicle. The surroundings may include the area in front of the vehicle, including the road surface ahead of the vehicle; likewise, it may include the area behind the vehicle (in particular, when the vehicle is reversing) ; it may include any space in the vicinity of the vehicle where obstacles or other road users may be present. The surroundings of the vehicle may extend to a distance of meters, tens of meters, or even hundreds of meters. The characterization is performed by determining distances to objects in the surroundings. While distance is a fundamental measurement parameter, estimates of derived variables such as velocity (including direction of motion) and acceleration of the detected objects may be determined on the basis of multiple distance measurements at different points in time. For complex objects, which may be recognized by combining information from multiple spatially diverse measurement points, additional

parameters such as orientation and rotation may also be derived. As all measurements are relative to the sensor, measurements of "fixed" objects may also provide information about the velocity, acceleration, orientation (pitch, yaw, roll), and rotation of the sensor, and thus of the vehicle onto which it is mounted.

The system comprises projection means **210** arranged for projecting a pattern of laser light towards the surroundings in a sequence of pulses; a detector **220** comprising a plurality of pixels, the detector **220** being configured for detecting light representing the pattern of laser light as reflected by the surroundings in synchronization with the sequence of pulses; and processing means **240** configured to calculate distances to objects **99** in the surroundings as a function of exposure values generated by the pixels in response to the detected light.

If the system works according to the time-of-f light (LIDAR) principle, the pixels **220** may be configured to generate the exposure values by accumulating, for all of the pulses of the sequence, a first amount of electrical charge representative of a first amount of light reflected by the objects **99** during a first predetermined time window **10** and a second electrical charge representative of a second amount of light reflected by the objects during a second predetermined time window **20**, the second predetermined time window **20** occurring after the first predetermined time window **10**.

The operating principle of such a LIDAR-based system is illustrated by the timing diagrams in Figures 2-4. For clarity reasons, only a single pulse of the pulse sequence which is repeated periodically is illustrated, which consists of a first time window **10** and a second time window **20**. The principle is described, by way of example, with reference to a projection means comprising a solid-state light source.

As can be seen in Figure 2, during the first time window **10**, the solid-state light source **210** is in its "ON" state, emitting the

pattern of light spots onto the scenery. During the second time window **20**, the solid-state light source **210** is in its "OFF" state.

The arrival of the reflected light at the detector **220** is delayed relative to the start of the projection by an amount of time that is proportional to the distance travelled (approximately 3.3 ns/m in free space) . Due to this delay, only a part of the reflected light will be detected at the first well **221** of the detector **220**, which is only activated during the first time window **10**. Thus, the charge accumulated in this first well during its period of activation (the first time window **10**) consists of a part representing only the noise and the ambient light impinging on the pixel prior to the arrival of the reflected pulse, and a part representing the noise, the ambient light, and the leading edge of the reflected pulse.

The latter part of the reflected pulse will be detected at the second well **222** of the detector **220**, which is only activated during the second time window **20**, which preferably immediately follows the first time window **10**. Thus, the charge accumulated in this second well during its period of activation (the second time window **20**) consists of a part representing the noise, the ambient light, and the trailing edge of the reflected pulse, and a part representing only the noise and the ambient light impinging on the pixel after the arrival of the reflected pulse.

The greater the distance between the reflecting object **99** and the system **200**, the smaller the proportion of the pulse that will be detected in the first well **221** and the larger the proportion of the pulse that will be detected in the second well **222**.

If the leading edge of the reflected pulse arrives after the closing of the first well **221** (i.e., after the end of the first time window **10**) , the proportion of the reflected pulse that can be detected in the second well **222** will decrease again with increasing time of flight delay.

The resulting amounts of charge **A**, **B** in each of the respective wells **221**, **222** for varying distances of the object **99** is shown in Figure 3b. To simplify the representation, the effect of the attenuation of light with distance, according to the inverse square law, has not been taken into account in the diagram. It is clear that for time of flight delays up to the combined duration of the first time window **10** and the second time window **20**, the time of flight delay can in principle unambiguously be derived from the values of **A** and **B**:

- For time of flight delays up to the duration of the first time window **10**, **B** is proportional to the distance of the object **99**. To easily arrive at a determination of the absolute distance, the normalized value **B/(B+A)** may be used, removing any impact of non-perfect reflectivity of the detected object and of the inverse square law.
- For time of flight delays exceeding the duration of the first time window **10**, **A** consists of daylight and noise contributions only (not illustrated), and **C-B** is substantially proportional (after correcting for the inverse square law) to the distance of the object **99**, where **C** is an offset value.

While Figures 2 and 3 illustrate the principle of the invention in relation to a single pulse emitted in the time window **10**, it shall be understood that the illustrated pulse is part of a sequence of pulses as defined above. Figure 4 schematically illustrates exemplary timing characteristics of such a sequence. As illustrated, the illumination scheme **40** consists of a repeated emission of a sequence **30** of individual pulses **10**. The width of the individual pulses **10** is determined by the maximal operating range. The entire sequence may be repeated at a frequency of, for example, 60 Hz.

Various optional features of a time-of-flight based sensing system are described in unpublished European patent application no. EP 15 191 288.8, in the name of the present applicant, the contents of which are incorporated by this reference for the purpose of

enabling the skilled person to include these features in embodiments of the present invention.

If the system works according to the triangulation principle, the processing means **240** may be adapted to determine the distances by determining a displacement of features of the detected light representing the pattern of laser light as reflected by the surroundings with reference to predetermined feature positions. Preferably, the projected pattern is a pattern of spots of laser light, and the distances are determined by determining a displacement of detected spots that represent the projected spots as reflected by objects in the surroundings, with reference to predetermined spot positions.

Various optional features of a triangulation based sensing system are disclosed in international patent application publication WO 2015/004213 A1 in the name of the present applicant, the contents of which are incorporated by this reference for the purpose of enabling the skilled person to include these features in embodiments of the present invention.

According to the invention, the detector **220** is further configured for detecting light forming a two-dimensional image of the surroundings at points in time that do not coincide with the sequence of pulses or at pixels that do not receive said light representing said pattern of laser light as reflected by said surroundings .

In view of the accuracy requirements of vehicular ranging systems, CMOS sensor arrays having a total array size in the order of 1 megapixel are typically selected. The inventors have found that despite the relatively coarse size of the pixels used in such sensors, in the order of 10 µm, the combined sensor is capable of yielding a surprisingly acceptable 2D image quality when used in combination with adequate optics to form a rudimentary digital camera .

The invention, and in particular the concept of detecting light forming a two-dimensional image of the surroundings at points in time that do not coincide with the sequence of pulses, is based *inter alia* on the insight of the inventors that in the time intervals between the ranging pulses, or between sequences of ranging pulses, the pixel array may be used to capture digital 2D images of the surroundings. In this way, two different functions, which provide complementary information, may be combined in a single sensor.

The invention, and in particular the concept of detecting light forming a two-dimensional image of the surroundings at pixels that do not receive said light representing said pattern of laser light as reflected by said surroundings, is further based on the insight of the inventors that as ranging systems rely on the detection of reflections of specific light patterns, such as line patterns or spot patterns, only a small subset of the total number of pixels is actually being used at any given time. This specific concept may be used when sufficient ambient light reaches the detector when the ranging function (projection and detection of a light pattern) is operational, such that the pixels which do not receive part of the projected pattern can form an image from the received light .

While the pattern-reflection based range sensing provides a depth map containing 3-dimensional information only at the points illuminated by the projected pattern of laser light, the 2D images captured in-between provide a visual snapshot of the entire scenery. The depth map can be registered to the 2D images, and depth information can be obtained for every pixel in the 2D images by interpolating the depth map values. As the 2D images and the 3D information are obtained from the same sensor, there is no parallax between the different images, which facilitates the registration .

Preferably, the interpolation of the depth map values is assisted by the pixel values in the 2D images. Thus, for example, an area

between different depth map values which corresponds to a regular luminance or color gradient in the 2D image, may be interpolated in the depth dimension by linear interpolation. An area between different depth map values which includes an abrupt step in the luminance or color value, may be interpolated by a stepwise constant depth value, with the step in the depth value is made to coincide with the step in the luminance or color value.

The combined 2D/3D image combines more information about the surroundings than either of the sources taken separately. A machine vision system may be supplied with the combined 2D/3D image to detect relevant features in the environment, such as pedestrians, vehicles, fixed objects, debris, any unevenness in the road surface, and the like.

The 2D images are preferably captured in timeslots occurring between *frames*, e.g. between sequences of pulses. Exemplary timing diagrams are shown in Figure 5. In diagram a (not according to the invention), 5 consecutive *frames* (each representing a sequence of pulses, for example a sequence 30 of Figure 2) are all used for 3D range sensing. In diagram d, one *frame* of the first four *frames* is replaced by a 2D image capturing timeslot, of the exact same duration as the remaining *frames*; hence, the overall cadence of the frames remains the same, but only 75% of the *frame* time slots are used for range sensing (the skilled person will appreciate that this figure may be varied according to the requirements of the application; the relative time reserved for range sensing may for example be 10%, 20%, 25%, 33%, 40%, 50%, 60%, 67%, 75%, 80%, etc.). In diagrams b and c, the time used for 2D image capturing is made longer and shorter than the range sensing *frames*, respectively.

Generally, the time used for 2D image capturing may be selected in function of the desired exposure time, which must be sufficiently long to accumulate a sufficient amount of light in the pixels and sufficiently short to avoid motion blur (when the sensor and/or objects in the surroundings are in motion). The time slot used for

2D image capturing may also be extended to allow consecutive capturing of light in different wavelength bands (e.g., red, green, and blue light, to generate an RGB image), as explained below with reference to Figure 7, diagram b.

As explained in great detail in the aforementioned patent applications WO 2015/004213 A1 and EP 15 191 288.8, several measures must be taken to filter out ambient light (in particular, sunlight) from the signal that reaches the sensor, such that the light that reaches the sensor is substantially limited to the desired reflection of the projected light pattern, in order to ensure accurate and long-range distance sensing. These measures include the use of a narrow bandpass filter, and optics that guide the incoming reflected light on a path that is substantially perpendicular to the narrow bandpass filter.

The measures required to optimize the range-sensing capabilities limit the usefulness of the pixel array as a 2D image camera. As the sensors is mounted on a vehicle, which, when in use, is normally moving, any increase of the exposure time to increase the total amount of light captured in a single exposure is limited by the acceptable amount of motion blur - in practice, this is a severe limitation.

In view of these negative effects, the inventors have found that the following optional features lead to better performance in the 2D image capturing.

A first solution consists of using a bandpass filter at the sensor side which can be electronically or electromechanically controlled to be active in synchronization with the pulse sequence and inactive at the points in time when the 2D images are captured.

A second solution consists of providing the system with illumination means configured to project a bundle of light onto the surroundings at the points in time that do not coincide with the sequence of pulses. Such illumination means may provide a

flash of illumination, as is often done in conventional photography in low light conditions. The projection means **210** and the illumination means may share a common light source, in particular a VCSEL array. This ensures that a "flash" can be emitted in the same wavelength band for which the narrow bandpass filter is optimized, thus maximizing the amount of light that will reach the pixel array. If the common light source is VCSEL array, the illumination means may further comprise an actively steered diffuser, configured to be activated at the points in time at which the 2D images are taken (which do not coincide with the sequence of pulses) , so as to diffuse light originating from the VCSEL array to form the desired bundle of light (instead of a series of spots) . The illumination means may also be integrated with the headlight assembly, whereby the light source must be chosen such that it provides sufficient light power in the part of the spectrum that can pass through the narrow bandpass filter at the sensor side.

In view of the above considerations, one particularly advantageous embodiment of the system according to the present invention operates according to the time-of-flight based principle described above, whereby a VCSEL array is provided to project a pulsed pattern of discrete spots onto the scenery to be characterized, the reflections of which are detected by a CMOS-based sensor array equipped with a narrow bandpass filter configured to permit substantially only the wavelength emitted by the VCSEL array to pass. A separate flash light emitting a bundle of light of the same wavelength (typically in a narrow wavelength range around 860 nm) is provided to illuminate the scenery at the moments when the 2D images are to be captured - by design, the light emitted by the flash light will also be able to pass through the narrow passband filter at the detector. Preferably, four out of every five time slots are used to project/detect ranging frames, and the remaining one out of every five time slots is used to capture 2D images.

In embodiments of the present invention, different pixels of the plurality of pixels of the detector **220** are provided with

different filters allowing light in different wavelength bands to reach the different pixels at the points in time. This is schematically illustrated in Figure 6, where a pixel array is shown with different pixels (or different wells of a pixel), provided with respective filters for near infrared (NIR) light, red light, green light, and blue light.

In other embodiments of the present invention, the plurality of pixels of the detector 220 are provided with a time-dependent filter allowing light in different wavelength bands to reach the plurality of pixels at different ones of the points in time. This is schematically shown in Figure 7, diagram a, where separate time slots are provided to capture red, green, and blue light; and in Figure 7, diagram b, where the time slot is extended to allow for consecutive capturing of red, green, and blue light in consecutive parts of the same time slot.

These sets of embodiments allow an RGB 2D image to be captured, which is suitable for rendering on a color display.

The present invention also pertains to a vehicle (in particular a road vehicle or a railway vehicle) comprising the system according to any of the preceding claims arranged so as to characterize an area surrounding the vehicle.

While the invention has been described hereinabove with reference to separate system and method embodiments, this was done for clarifying purposes only. The skilled person will appreciate that features described in connection with the system or the method alone, can also be applied to the method or the system, respectively, with the same technical effects and advantages. Furthermore, the scope of the invention is not limited to these embodiments, but is defined by the accompanying claims.

Claims

1. A system for characterizing surroundings of a vehicle, the system comprising:

- projection means (210) arranged for projecting a pattern of laser light towards said surroundings in a sequence of pulses, said pattern of laser light comprising a pattern of discrete spots;
- a detector (220) comprising a plurality of pixels, said detector (220) being configured for detecting light representing said pattern of laser light as reflected by said surroundings in synchronization with said sequence of pulses; and
- processing means (240) configured to calculate distances to objects (99) in said surroundings as a function of exposure values generated by said pixels in response to said detected light;

wherein said detector (220) is further configured for detecting light forming a two-dimensional image of said surroundings at points in time that do not coincide with said sequence of pulses or at pixels that do not receive said light representing said pattern of laser light as reflected by said surroundings.

2. The system according to claim 1, wherein said pixels (220) are configured to generate said exposure values by accumulating, for all of the pulses of said sequence, a first amount of electrical charge representative of a first amount of light reflected by said objects (99) during a first predetermined time window (10) and a second electrical charge representative of a second amount of light reflected by said objects during a second predetermined time window (20), said second predetermined time window (20) occurring after said first predetermined time window (10).

3. The system according to claim 1, wherein said processing means (240) are adapted to determine said distances by determining a displacement of features of said detected light representing said

pattern of laser light as reflected by said surroundings with reference to predetermined feature positions.

4. The system according to any of the preceding claims, comprising illumination means configured to project a bundle of light onto said surroundings at said points in time that do not coincide with said sequence of pulses.

5. The system according to claim 4, wherein said projection means (210) and said illumination means share a common light source.

6. The system according to claim 5, wherein said common light source comprises a VCSEL array, and wherein said illumination means further comprises an actively steered diffuser, configured to be activated at said points in time that do not coincide with said sequence of pulses, so as to diffuse light originating from said VCSEL array to form said bundle.

7. The system according to any of the preceding claims, wherein said plurality of pixels of said detector (220) are provided with a time-dependent filter allowing light in different wavelength bands to reach said plurality of pixels at different ones of said points in time.

8. The system according to any of the preceding claims, wherein different pixels of said plurality of pixels of said detector (220) are provided with different filters allowing light in different wavelength bands to reach said different pixels at said points in time.

9. A vehicle comprising the system according to any of the preceding claims arranged so as to characterize an area surrounding said vehicle.

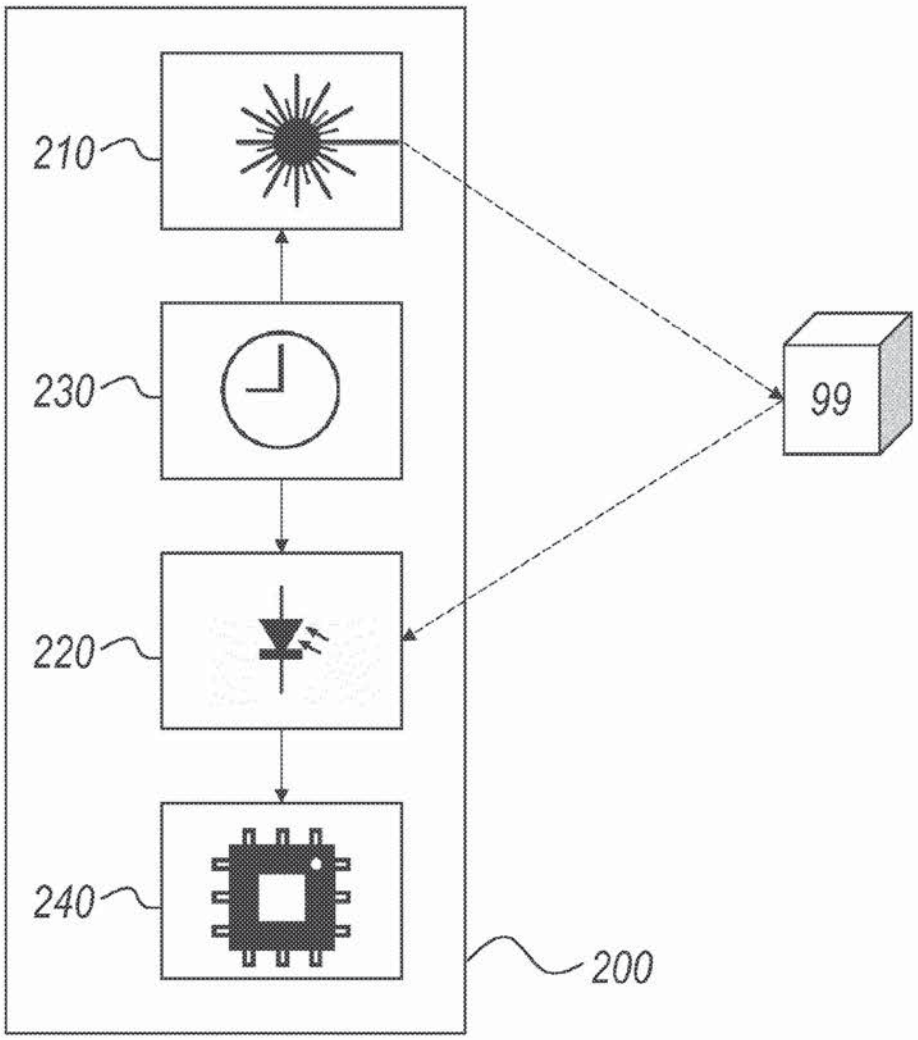


Fig. 1

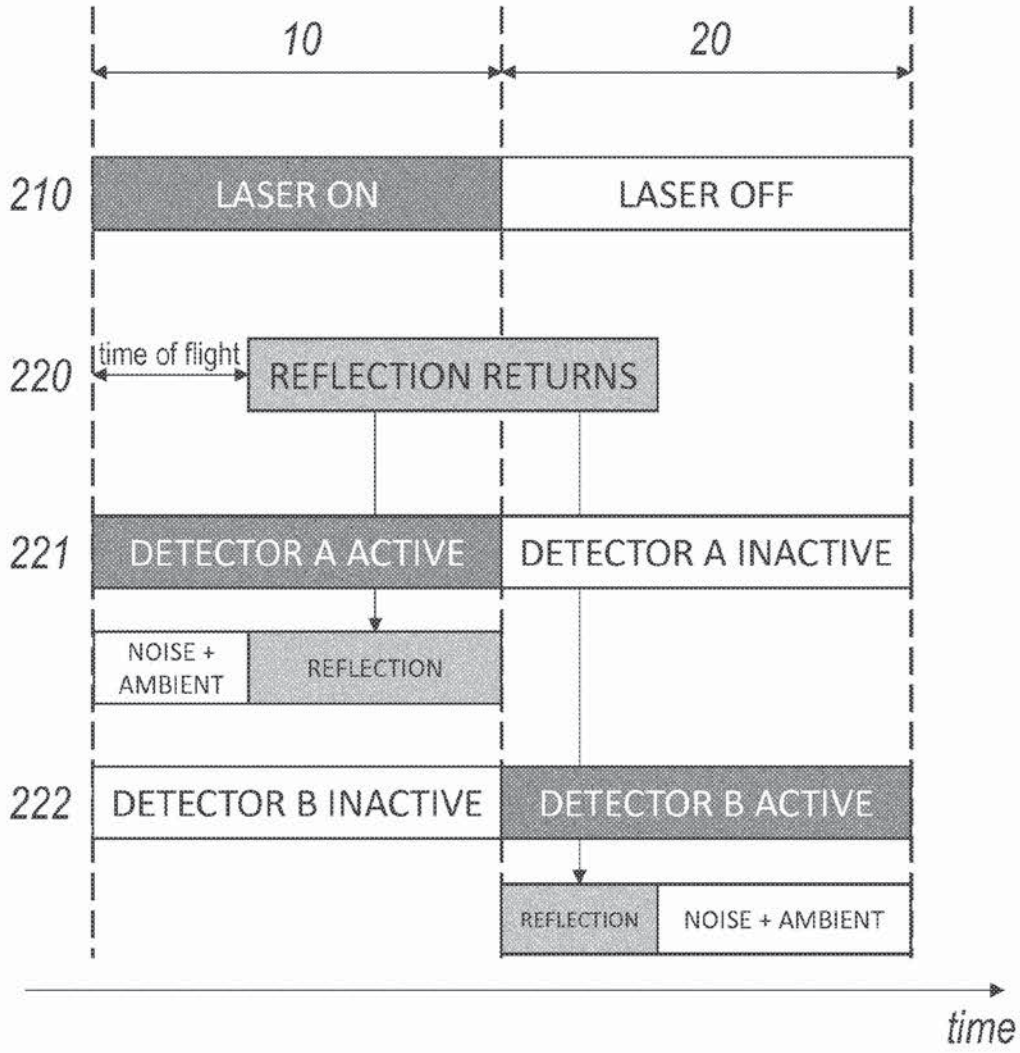

10
20
210
LASER ON
LASER OFF
220
time of flight
REFLECTION RETURNS
221
DETECTOR A ACTIVE
DETECTOR A INACTIVE
NOISE + AMBIENT
REFLECTION
222
DETECTOR B INACTIVE
DETECTOR B ACTIVE
REFLECTION
NOISE + AMBIENT
time

Fig. 2

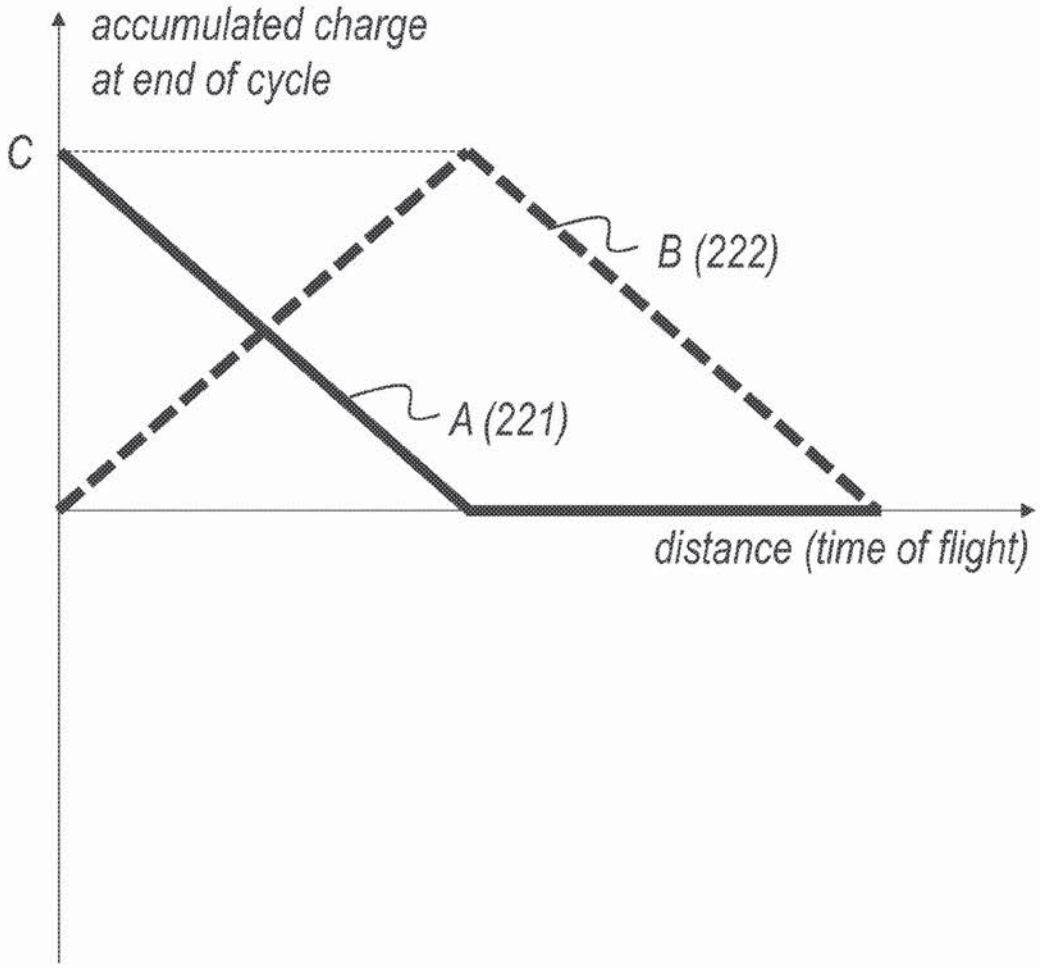

accumulated charge
at end of cycle
C
B (222)
A (221)
distance (time of flight)

Fig. 3

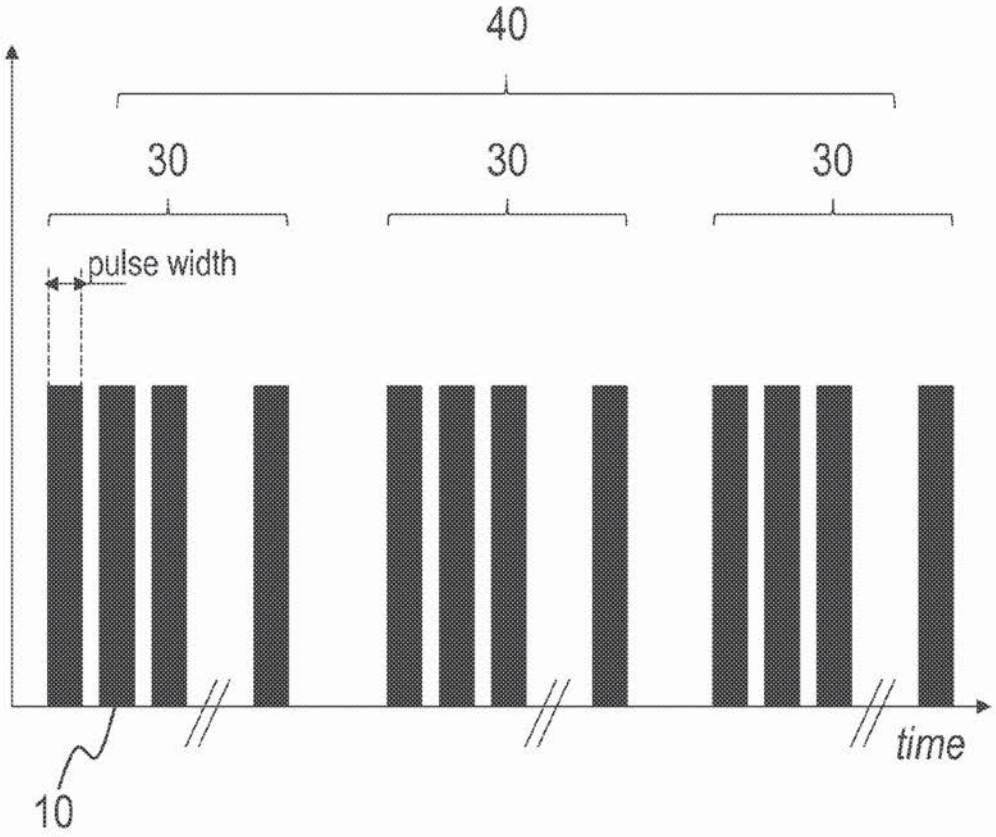


Fig. 4

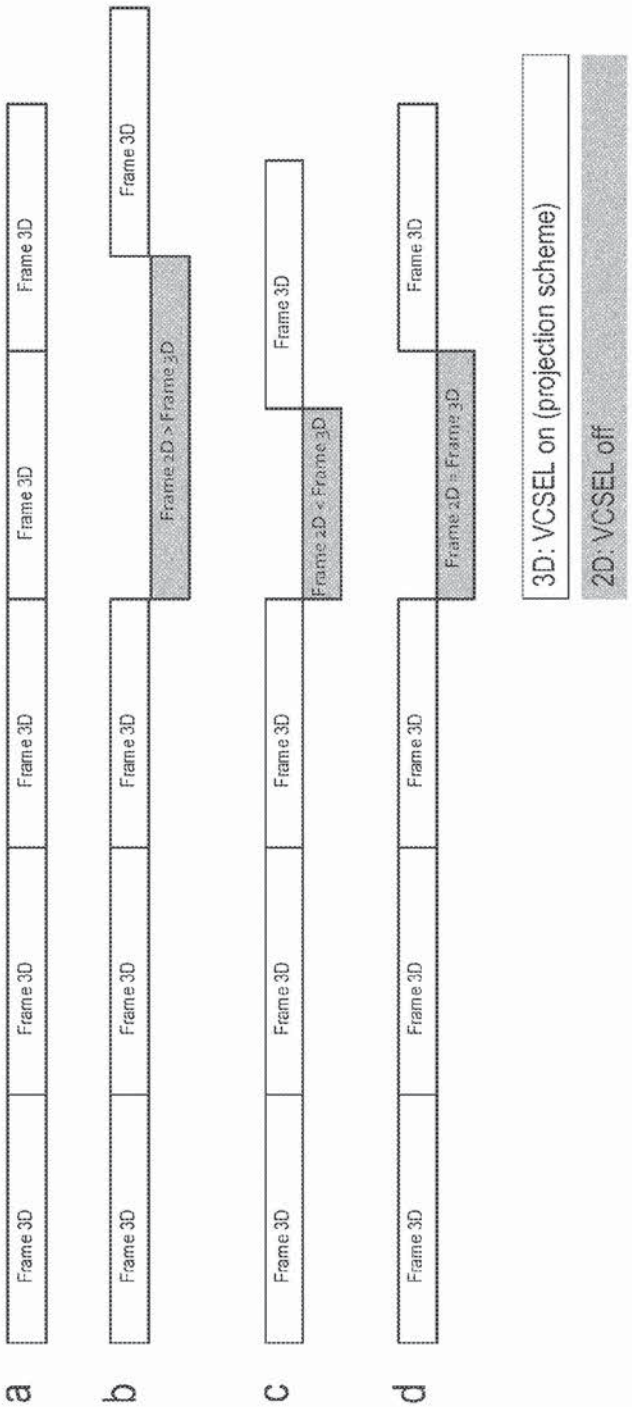

a
b
c
d
Frame 3D
Frame 2D > Frame 3D
Frame 2D < Frame 3D
Frame 2D = Frame 3D
3D: VCSEL on (projection scheme)
2D: VCSEL off

Fig. 5

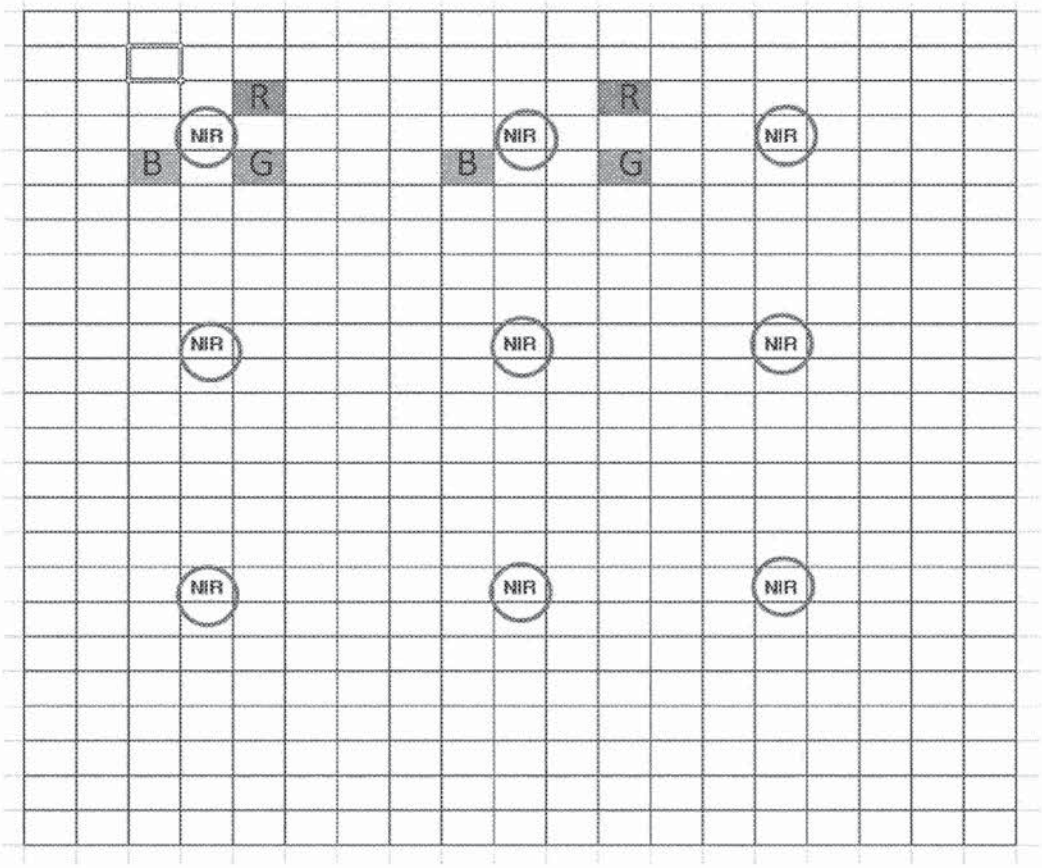
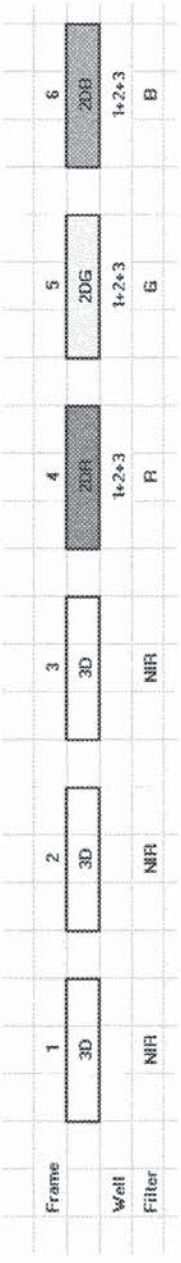
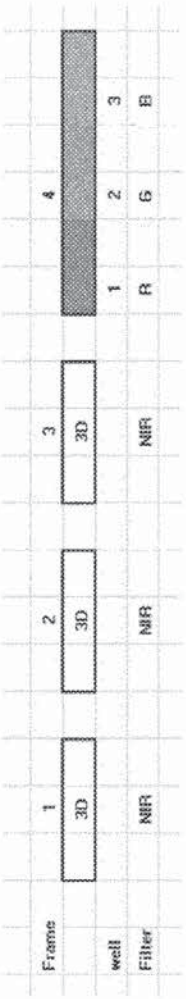


Fig. 6


Frame
well
Filter
1
3D
NIR
2
3D
NIR
3
3D
NIR
4
2DR
1+2+3
R
5
2DG
1+2+3
G
6
2DB
1+2+3
B

a


Frame
well
Filter
1
3D
NIR
2
3D
NIR
3
3D
NIR
4
1
R
2
G
3
B

b

Fig. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/050080

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S17/10 G01S17/89 G01S17/93
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01S

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal , INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/319347 A1 (COTTRELL WILLIAM [US]) 5 November 2015 (2015-11-05)	1-4,8,9
Y	paragraphs [0001] - [0007]	5-7
	paragraphs [0013] - [0030]	

X	US 2016/266255 A1 (NISHIKAWA YUYA [JP] ET AL) 15 September 2016 (2016-09-15)	1,3,4,8, 9
Y	paragraphs [0006] , [0012]	5-7
	paragraphs [0027] - [0052]	

X	WO 2015/162278 A1 (CATHX RES LTD [IE]) 29 October 2015 (2015-10-29)	1,3,4,9
Y	paragraph [0003]	5-7
	paragraphs [0026] - [0035]	
	paragraphs [0053] - [0065]	

	-/-	

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" documentwhich may throw doubts on priority claim(s) orwhich is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 April 2018	19/04/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Hirsch , Stefanie

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/050080

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2016/020073 A1 (CEMB S P A [IT]) 11 February 2016 (2016-02-11) pages 1-8	5,6
Y	US 2016/295133 A1 (RUDMANN HARTMUT [CH] ET AL) 6 October 2016 (2016-10-06) paragraphs [0002] - [0009]	7

1

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2018/050080

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2015319347 A1	05-11-2015	NONE	
US 2016266255 A1	15-09-2016	JP 2016166784 A	15-09-2016
		US 2016266255 A1	15-09-2016
WO 2015162278 A1	29-10-2015	AU 2015250746 A1	15-12-2016
		CA 2946788 A1	29-10-2015
		EP 3133979 A1	01-03-2017
		US 2017048494 A1	16-02-2017
		WO 2015162278 A1	29-10-2015
WO 2016020073 A1	11-02-2016	CN 106461378 A	22-02-2017
		EP 3074721 A1	05-10-2016
		US 2018038685 A1	08-02-2018
		WO 2016020073 A1	11-02-2016
US 2016295133 A1	06-10-2016	NONE	

Form PCT/ISA/210 (patent family annex) (April 2005)

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
12 April 2018 (12.04.2018)

W!P O | PCT

(10) International Publication Number
WO 2018/065426 A1

(51) International Patent Classification:
G01S 17/10 (2006.01) *G01S 7/487* (2006.01)
G01S 17/89 (2006.01) *G01S 17/93* (2006.01)
G01S 7/486 (2006.01) *G01S 7/481* (2006.01)

(21) International Application Number:
PCT/EP2017/075093

(22) International Filing Date:
03 October 2017 (03.10.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
16192105.1 03 October 2016 (03.10.2016) EP

(71) Applicant: **XENOMATIX NV** [BE/BE]; Esperantolaan 4, B-3001 Leuven (BE).

(72) Inventors: **VAN DYCK, Dirk;** Kleine Grippe 37, B-2630 Aartselaar (BE). **PAESEN, Rik;** Helstraat 82, B-3590 Diepenbeek (BE).

(74) Agent: **IPLODGE BVBA;** Technologielaan 9, B-3001 Heverlee (BE).

(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.

(54) **Title:** METHOD FOR SUBTRACTING BACKGROUND LIGHT FROM AN EXPOSURE VALUE OF A PIXEL IN AN IMAGING ARRAY, AND PIXEL FOR USE IN SAME

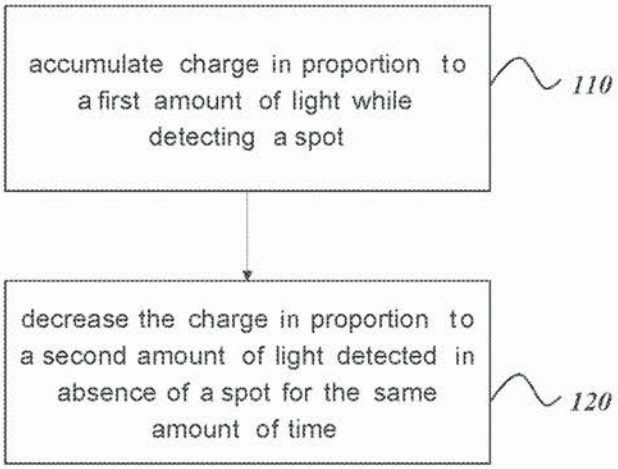


Fig. 1

(57) **Abstract:** The invention pertains to a method for subtracting background light from an exposure value of a pixel in an imaging array, and pixel for use in same The invention pertains to a method for subtracting background light from an exposure value of a first pixel in an imaging array, said first pixel receiving a reflection of a spot from a scenery illuminated by a periodically pulsed pattern of spots, said periodically pulsed pattern comprising in alternation an illuminated phase and a non-illuminated phase, the method comprising: accumulating in said first pixel a charge in proportion to a first quantity of incident light, received in said first pixel while detecting said spot during a predetermined amount of time; and decreasing said charge in proportion to a second quantity of incident light received during said predetermined amount of time in absence of said spot. The invention also pertains to a pixel and an imaging array.

WO 2018/065426 A1

[Continued on nextpage]

(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).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

Method for subtracting background light from an exposure value of a pixel in an imaging array, and pixel for use in same

Field of the Invention

The present invention pertains to the field of imaging systems, and in particular to a method for subtracting background light from an exposure value of a pixel in an imaging array, and to a pixel for use in such a method. The present invention may be used *inter alia* in systems for determining a distance to an object, in particular to time-of-flight based sensing systems to be used for the characterization of a scene or a part thereof.

Background

In the field of remote sensing technology, mainly in the usage of making high-resolution maps of the surroundings, to be used in many control and navigation applications such as but not limited to the automotive and industrial environment, gaming applications, and mapping applications, it is known to use time-of-flight based sensing to determine the distance of objects from a sensor. Time-of-flight based techniques include the use of RF modulated sources, range gated imagers, and direct time-of-flight (DToF) imagers. For the use of RF modulated sources and range gated imagers, it is necessary to illuminate the entire scene of interest with a modulated or pulsed source. Direct time-of-flight systems, such as most LIDARs, mechanically scan the area of interest with a pulsed beam, the reflection of which is sensed with a pulse detector.

In order to be able to correlate an emitted RF modulated signal with the detected reflected signal, the emitted signal must meet a number of constraints. In practice, these constraints turn out to make the RF modulated systems highly impractical for use in vehicular systems: the attainable range of detection is very limited for signal intensities that are within conventional safety limits and within the power budget of regular vehicles.

A direct TOF (DToF) imager, as used in most LIDAR systems, comprises a powerful pulsed laser (operating in a nanosecond pulse regime) , a mechanical scanning system to acquire from the ID point measurement a 3D map, and a pulse detector. Systems of this type are presently available from vendors including Velodyne Lidar of Morgan Hill, California. The Velodyne HDL-64E, as an example of state-of-the-art systems, uses 64 high-power lasers and 64 detectors (avalanche diodes) in a mechanically rotating structure at 5 to 15 rotations per second. The optical power required by these DToF LIDAR systems is too high to be obtained with semiconductor lasers, whose power is in the range of five to six orders of magnitude lower. In addition, the use of mechanically rotating elements for scanning purposes limits the prospects for miniaturization, reliability, and cost reduction of this type of system.

United States Patent application publication no. 2015/0063387 in the name of Trilumina discloses a VCSEL delivering a total energy of 50 mW in a pulse having a pulse width of 20 ns. The commercially available Optek OPV310 VCSEL delivers a total energy of 60 mW in a pulse having a duration of 10 ns and it can be estimated by extrapolation to have a maximum optical output power of 100 mW. This value is only realized under very stringent operating conditions, meaning optimal duty cycle and short pulse width so as to avoid instability due to thermal problems. Both the Trilumina disclosure and the Optek system illustrate that continuous-wave VCSEL systems are reaching their physical limits with respect to optical peak power output, due to thermal constraints inherently linked to the VCSEL design. At these pulse energy levels, and using ns pulses as presently used in DToF applications, the mere number of photons that can be expected to be usefully reflected by an object at a distance of 120 m is so low that it defeats detection by means of conventional semiconductor sensors such as CMOS or CCD or SPAD array. Thus, increasing the VCSEL power outputs by 5 or 6 orders of magnitude,

as would be required to extend the range of the known DToF systems, is physically impossible.

Even the use of avalanche diodes (AD or SPAD), which are theoretically sufficiently sensitive to capture the few returning photons, cannot be usefully deployed in the known LIDAR system architectures. A solid state implementation of an array of SPADs must be read out serially. A high number of SPADs is required to achieve the desired accuracy. The serial read-out constraints of the solid state implementation limit the bandwidth of the system turning it inappropriate for the desired accuracy. For accuracies such as that of the Velodyne system (0.02 m to 0.04 m, independent of distance), the required read-out data rate exceeds the practically achievable bandwidth in case of today's IC implementation. For operation at 120 m, a SPAD array of 500x500 pixels is required, which, in an IC-based implementation, must be read-out serially. For the same precision as the aforementioned Velodyne system, it would require 1000 pulses per millisecond and hence 1000 frames per millisecond, translating into a readout rate of 250 Gigapixels per second. This is believed to be technically unfeasible in the context of current SPAD IC technology.

The paper by Neil E. Newman et al., "High Peak Power VCSELs in Short Range LIDAR Applications", *Journal of Undergraduate Research in Physics*, 2013, http://www.jurp.org/2 013/12 017EXR.pdf, describes a VCSEL-based LIDAR application. The paper states that the maximum output power of the described prototype system was not great enough to do wide-field LIDAR at a range greater than 0.75 m. With a relatively focused beam (0.02 m spot size at 1 m distance), the authors were able to range a target object at a distance of up to 1 m.

The above examples clearly indicate that the optical power emitted by present semiconductor lasers cannot meet the power requirements necessary for operations in the known LIDAR systems to be of practical use in automotive applications (e.g. for ranges up to 120 m).

United States patent no. 7,544,945 in the name of Avago Technologies General IP (Singapore) Pte. Ltd., discloses vehicle-based LIDAR systems and methods using multiple lasers to provide more compact and cost-effective LIDAR functionality. Each laser in an array of lasers can be sequentially activated so that a corresponding optical element mounted with respect to the array of lasers produces respective interrogation beams in substantially different directions. Light from these beams is reflected by objects in a vehicle's environment, and detected so as to provide information about the objects to vehicle operators and/or passengers. The patent provides a solid state projector in which the individual lasers are consecutively activated in order to replace the known mechanical scanning in the known DToF LIDAR systems.

A high-accuracy medium-range surround sensing system for vehicles that does not use time-of-flight detection, is known from international patent application publication WO 2015/004213 A1 in the name of the present applicant. In that publication, the localization of objects is based on the projection of pulsed radiation spots and the analysis of the displacement of detected spots with reference to predetermined reference spot positions. More in particular, the system of the cited publication uses triangulation. However, the accuracy that can be achieved correlates with the triangulation base, which limits the further miniaturization that can be achieved.

US patent application publication no. US 2012/0038903 A1 discloses methods and systems for adaptively controlling the illumination of a scene. In particular, a scene is illuminated, and light reflected from the scene is detected. Information regarding levels of light intensity received by different pixels of a multiple pixel detector, corresponding to different areas within a scene, and/or information regarding a range to an area within a scene, is received. That information is then used as a feedback signal to control levels of illumination within the scene. More

particularly, different areas of the scene can be provided with different levels of illumination in response to the feedback signal .

European patent application publication no. EP 2 322 953 A1 discloses a distance image sensor capable of enlarging the distance measurement range without reducing the distance resolution. A radiation source provides first to fifth pulse trains which are irradiated to the object as radiation pulses in the first to fifth frames arranged in order on a time axis. In each of the frames, imaging times are prescribed at points of predetermined time from the start point of each frame, also the pulses are shifted respectively by shift amounts different from each other from the start point of the first to fifth frames. A pixel array generates element image signals each of which has distance information of an object in distance ranges different from each other using imaging windows A and B in each of five frames. A processing unit generates an image signal by combining the element image signals. Since five times-of-flight measurement are used, the width of the radiation pulse does not have to be increased to obtain distance information of the object in a wide distance range, and the distance resolution is not reduced.

European patent application publication no. EP 2 290 402 A1 discloses a range image sensor which is provided on a semiconductor substrate with an imaging region composed of a plurality of two-dimensionally arranged units, thereby obtaining a range image on the basis of charge quantities output from the units. One of the units is provided with a charge generating region (region outside a transfer electrode) where charges are generated in response to incident light, at least two semiconductor regions which are arranged spatially apart to collect charges from the charge generating region, and a transfer electrode which is installed at each periphery of the semiconductor region, given a charge transfer signal different in phase, and surrounding the semiconductor region.

The article by Shoji Kawahito et al., "A CMOS Time-of-Flight Range Image Sensor With Gates-on-Field-Oxide Structure", *IEEE Sensors Journal*, Vol. 7, no. 12, p. 1578-1586, discloses a type of CMOS time-of-flight (TOS) range image sensor using single-layer gates on field oxide structure for photo conversion and charge transfer. This structure allows the realization of a dense TOF range imaging array with 15 x 15 μm^2 pixels in a standard CMOS process. Only an additional process step to create an n-type buried layer which is necessary for high-speed charge transfer is added to the fabrication process. The sensor operates based on time-delay dependent modulation of photocharge induced by back reflected infrared light pulses from an active illumination light source. To reduce the influence of background light, a small duty cycle light pulse is used and charge draining structures are included in the pixel. The TOF sensor chip fabricated measures a range resolution of 2.35 cm at 30 frames per second an improvement to 0.74 cm at three frames per second with a pulse width of 100 ns.

All systems that rely on the detection of structured light emitted onto the scenery to be sensed, require a way to distinguish illuminated portions of the scenery from non-illuminated portions, despite the presence of ambient light. Hence, there is a continuing need to obtain methods and pixels that allow reliable removal of the background illumination component from an exposure value.

Summary of the Invention

According to an aspect of the present invention, there is provided a method for subtracting background light from an exposure value of a first pixel in an imaging array, said first pixel receiving a reflection of a spot from a scenery illuminated by a periodically pulsed pattern of spots, said periodically pulsed pattern comprising in alternation an illuminated phase and a non-illuminated phase, the method comprising: accumulating in said first pixel a charge in proportion to a first quantity of incident light, received in said first pixel while detecting said spot

during a predetermined amount of time; and decreasing said charge in proportion to a second quantity of incident light received during said predetermined amount of time in absence of said spot.

It is an advantage of the present invention that the background illumination is detected with components that are virtually identical to the components that detect the useful signal, and that both the background illumination and the useful signal are integrated over the same amount of time. In this way, an optimal pair of signals is obtained for subtraction.

In an embodiment of the method according to the present invention, the second quantity of incident light comprises light received in said first pixel during said predetermined amount of time in the non-illuminated phase.

It is an advantage of this embodiment that the background illumination is detected with components that are exactly the same as the components that detect the useful signal, which detect light originating from a single location in the scenery (apart from possibly a slight shift due to movement of the sensor) , such that the comparison between the illuminated phase and the non-illuminated phase provides a subtraction of the background illumination at that very location.

In another embodiment of the method according to the present invention, the second quantity of incident light comprises light received, during said accumulating, in a second pixel of the pixel array, the second pixel being at a sufficient distance from the first pixel so as not to be illuminated by said spot.

It is an advantage of this embodiment that the background illumination is detected at the same time as the useful signal, such that the subtraction of the background illumination is not sensitive to changes in the level of background illumination over time .

According to an aspect of the present invention, there is provided a pixel adapted for use as said first pixel in the method described above.

In an embodiment, the pixel comprises a capacitor for storing said charge, said capacitor having a first side and a second side, wherein said accumulating comprises transferring charges to said first side, and wherein said decreasing comprises transferring charges to said second side.

It is an advantage of this embodiment of the pixel according to the invention that it implements the inventive method of background subtraction in a very compact and reliable way, and without relying on additional digital computations.

According to an aspect of the present invention, there is provided an imaging array comprising a plurality of pixels as described above .

According to an aspect of the present invention, there is provided a system for determining a distance to an object comprising: a solid-state light source arranged for projecting a pattern of spots of laser light towards the object in a sequence of pulses; a detector comprising the imaging array as described above, the detector being configured for detecting light representing the pattern of spots as reflected by the object in synchronization with the sequence of pulses; and processing means configured to calculate the distance to the object as a function of exposure values generated by the pixels in response to the detected light; wherein the pixels are configured to generate the exposure values by accumulating, for each pulse of the sequence, a first amount of electrical charge representative of a first amount of light reflected by the object during a first predetermined time window and a second electrical charge representative of a second amount of light reflected by the object during a second predetermined time window, the second predetermined time window occurring after the first predetermined time window.

The inventors have found that the improved background subtraction method of the present invention can contribute to achieving the demanding power/performance requirements of automotive applications with a compact, semiconductor based time-of-flight based ranging system.

Brief Description of the Figures

These and other aspects and advantages of the present invention will now be described in more detail with reference to the accompanying drawings, in which:

Figure 1 represents a flow chart of an embodiment of the method according to the present invention;

Figure 2 schematically represents an embodiment of the pixel according to the present invention;

Figure 3 represents a flow chart of an embodiment of the method according to the present invention;

Figure 4 schematically represents an embodiment of the system according to the present invention;

Figure 5 represents a timing diagram for light projection and detection in embodiments of the present invention.

Detailed Description of Embodiments

Figure 1 represents a flow chart of an embodiment of the method for subtracting background light from an exposure value of a first pixel in an imaging array according to the present invention. The first pixel receives a reflection of a spot from a scenery illuminated by a periodically pulsed pattern of spots, the periodically pulsed pattern comprising in alternation an illuminated phase and a non-illuminated phase.

The method comprises accumulating **110** in the first pixel a charge in proportion to a first quantity of incident light, received in the first pixel while detecting the spot during a predetermined amount of time. The term "accumulating" is used herein to designate both an operation of an electronic circuit capable of collecting cumulative amounts of charge, and a mathematical operation carried out by digital computation means.

To remove the infuence of the ambient light from the exposure value, the method further comrpises decreasing **120** the accumulated charge in proportion to a second quantity of incident light received during the same predetermined amount of time, but in absence of a spot.

The second quantity of incident light may be obtained by receiving light the same pixel during an equal amount of time in the non-illuminated phase of the pulsed pattern. Alternatively, the second quantity of incident light may be obtained by receiving light simultaneously with the receiving of the spot, but in a different pixel of the pixel array. This variant relies on the fact that the projected pattern consists of distinct spots, and requires that the second pixel be at a sufficient distance from the first pixel so as not to be illuminated by the same spot.

Figure 2 schematically represents an embodiment of the pixel according to the present invention. The pixel is suitable for use in the method described above, and may be part of an imaging array .

The pixel comprises a capacitor **130** for storing the charge, said capacitor having a first side **130a** and a second side **130b.** The accumulating **110** comprises transferring charges to the first side **130a,** and the decreasing **120** comprises transferring charges to said second side **130b.** Subsequently, the voltage over the capacity **130** is measured, which represents the difference between the laser spot induced charges and the background charges.

The reaons for the presence of a second capacitor and a second pair of wells at the opposite side of the light sensitive element (righthand side of Figure 2, leading to "B signal") will become apparent from the following description of the range-gating method.

The inventors have found that the pixel array according to the present invention can advantageously be applied in a novel type of ranging system which aims to achieve the same power/performance characteristics with a compact, semiconductor based time-of-flight based system. Accordingly, an aspect of the present invention concerns a ranging system comprising the pixel array described above.

In this aspect of the invention, the limitations of the existing LIDAR-based systems are overcome by changing the way the time-of-flight based system operates. The total amount of light energy emitted for each time-of-flight measurement (and thus, the number of photons available for detection at the detector for each time-of-flight measurement) may be increased by increasing the duration of individual pulses and by producing a virtual "composite pulse", consisting of a sequence of a large number of individual pulses. This bundling of extended pulses allowed the inventors to obtain the required amount of light energy (photons) for the desired operational range with low-power VCSELs.

Where an individual pulse of pre-existing LIDAR systems may have a duration of 1 ns, the presently described systems benefit from a substantially longer pulse duration to partially compensate for the relatively low power level of semiconductor lasers such as VCSELs; in embodiments of the present invention, individual pulses within a sequence may have an exemplary duration of 1 µs (this is one possible value, chosen here to keep the description clear and simple; more generally, in embodiments of the present invention, the pulse duration may for example be 500 ns or more, preferably 750 ns or more, most preferably 900 ns or more). In an exemplary

system according to the present invention, a sequence may consist of 1000 pulse cycles, thus adding up to a duration of 1 ms. Given the fact that light would need approximately 0.66 µs to travel to a target at a distance of 100 m and back to the detector, it is possible to use composite pulses of this duration for ranging at distance of this order of magnitude; the skilled person will be able to adjust the required number of pulse cycles in function of the selected pulse width and the desired range. The detection of the sequence preferably comprises detecting the individual pulses in synchronization with the VCSEL-based light source, and accumulating the charges generated in response to the incoming photons at the pixel well level for the entire sequence prior to read-out. The term "exposure value" is used hereinafter to designate the value representative of the charge (and thus of the amount of light received at the pixel) integrated over the sequence. The sequence emission and detection may be repeated periodically .

The ranging system of the present invention operates by using range gating. Range gated imagers integrate the detected power of the reflection of the emitted pulse for the duration of the pulse. The amount of temporal overlap between the pulse emission window and the arrival of the reflected pulse depends on the return time of the light pulse, and thus on the distance travelled by the pulse. Thus, the integrated power is correlated to the distance travelled by the pulse. The present invention uses the principle of range gating, as applied to the sequences of pulses described hereinabove. In the following description, the integration of individual pulses of a sequence at the level of a picture element to obtain a measurement of the entire sequence is implicitly understood.

Figure 3 represents a flow chart of an applicable ranging method. Without loss of generality, the ranging method is described with reference to a range gating algorithm. In a first time window **10**, the method comprises projecting **110** a pattern of spots of laser light (e.g. a regular or an irregular spatial pattern of spots)

from a light source comprising a solid-state light source **210** onto any objects in the targeted area of the scenery. The spatial pattern is repeatedly projected in a sequence of pulses.

As indicated above, the solid-state light source may comprise a VCSEL array or a laser with a grating adapted to produce the desired pattern. In order for the system to operate optimally, even at long ranges and with high levels of ambient light (e.g., in daylight) , a VCSEL for use in embodiments of the present invention is preferably arranged to emit a maximum optical power per spot per unit of area. Thus, lasers with a good beam quality (low M2-factor) are preferred. More preferably, the lasers should have a minimal wavelength spread; a particularly low wavelength spread can be achieved with monomode lasers. Thus, substantially identical pulses can reproducibly be generated, with the necessary spatial and temporal accuracy.

During the same time window in which a pulse is emitted, or in a substantially overlapping time window, a first amount of light representing the pattern of spots as reflected by the object of interest is detected **120** at a detector, which is preferably arranged as near as possible to the light source. The synchronicity or near synchronicity between the projection **110** of the spot pattern and the first detection **120** of its reflection, is illustrated in the flow chart by the side-by-side arrangement of these steps. In a subsequent second predetermined time window **20**, a second amount of light representing the reflected light spot is detected **130** at the detector. During this second window **20**, the solid-state light source is inactive. The distance to the object can then be calculated **140** as a function of the first amount of reflected light and the second amount of reflected light.

The first predetermined time window **10** and the second predetermined time window **20** are preferably back-to-back windows of substantially equal duration, to facilitate noise and ambient light cancellation by subtracting one of the detected amounts from

the other one. An exemplary timing scheme will be described in more detail below in conjunction with Figure 5.

The detector comprises a pixel array as described above, which is configured to perform background light subtraction as described in connection with Figures 1 and 2, with adequate optics arranged to project an image of the scenery (including the illuminated spots) onto the picture element.

The term "picture element" as used herein may refer to an individual light-sensitive area or well of a pixel, or to an entire pixel (which may comprise multiple wells, see below). For every given projected spot, the detecting **120** of the first amount of light and the detecting **130** of the second amount of light occurs at the same one or the same group of the plurality of picture elements.

Without loss of generality, each of the picture elements may be a pixel comprising at least two charge storage wells **221, 222,** such that the detecting **120** of the first amount of light and the detecting **130** of the second amount of light can occur at the respective charge storage wells **221, 222** of the same pixel or pixel group.

Figure 4 schematically represents an embodiment of the system according to the present invention, in relation to an object **99** in the scenery of interest. The system **200** comprises a solid-state light source **210** for projecting a pattern of a sequence of spots, which may be repeated periodically, onto the object **99.** A detector **220** is arranged near the light source and configured to detect light reflected by the object.

The light beam bouncing off the object **99** is illustrated as an arrow in dashed lines, travelling from the light source **210** to the object **99** and back to the detector **220.** It should be noted that this representation is strictly schematic, and not intended to be indicative of any actual relative distances or angles.

A synchronization means **230**, which may include a conventional clock circuit or oscillator, is configured to operate the solid-state light source **210** so as to project the pattern of spots onto the object during first predetermined time windows **10** and to operate the detector **220** so as to detect a first amount of light representing the light spot(s) reflected by the object **99** at substantially the same time. It further operates the detector **220** to detect a second amount of light representing the light spots reflected by the object **99**, during respective subsequent second predetermined time windows **20**. Appropriate processing means **240** are configured to calculate the distance to the object as a function of the first amount of reflected light and the second amount of reflected light.

Figure 5 represents a timing diagram for light projection and detection in embodiments of the present invention. For clarity reasons, only a single pulse of the pulse sequence which is repeated periodically of Figure 3 is illustrated, which consists of a first time window **10** and a second time window **20**.

As can be seen in Figure 5a, during the first time window **10**, the solid-state light source **210** is in its "ON" state, emitting the pattern of light spots onto the scenery. During the second time window **20**, the solid-state light source **210** is in its "OFF" state.

The arrival of the reflected light at the detector **220** is delayed relative to the start of the projection by an amount of time that is proportional to the distance travelled (approximately 3.3 ns/m in free space) . Due to this delay, only a part of the reflected light will be detected at the first well **221** of the detector **220**, which is only activated during the first time window **10**. Thus, the charge accumulated in this first well during its period of activation (the first time window **10**) consists of a part representing only the noise and the ambient light impinging on the pixel prior to the arrival of the reflected pulse, and a part

representing the noise, the ambient light, and the leading edge of the reflected pulse.

The latter part of the reflected pulse will be detected at the second well **222** of the detector **220**, which is only activated during the second time window **20**, which preferably immediately follows the first time window **10**. Thus, the charge accumulated in this second well during its period of activation (the second time window **20**) consists of a part representing the noise, the ambient light, and the trailing edge of the reflected pulse, and a part representing only the noise and the ambient light impinging on the pixel after the arrival of the reflected pulse.

The greater the distance between the reflecting object **99** and the system **200**, the smaller the proportion of the pulse that will be detected in the first well **221** and the larger the proportion of the pulse that will be detected in the second well **222**.

If the leading edge of the reflected pulse arrives after the closing of the first well **221** (i.e., after the end of the first time window **10**), the proportion of the reflected pulse that can be detected in the second well **222** will decrease again with increasing time of flight delay.

The resulting amounts of charge A, B in each of the respective wells **221**, **222** for varying distances of the object **99** are shown in Figure 5b. To simplify the representation, the effect of the attenuation of light with distance, according to the inverse square law, has not been taken into account in the diagram. It is clear that for time of flight delays up to the combined duration of the first time window **10** and the second time window **20**, the time of flight delay can in principle unambiguously be derived from the values of A and B:

- For time of flight delays up to the duration of the first time window **10**, B is proportional to the distance of the object **99**. To easily arrive at a determination of the absolute distance, the normalized value B/(B+A) may be used,

removing any impact of non-perfect reflectivity of the detected object and of the inverse square law.

- For time of flight delays exceeding the duration of the first time window **10**, **A** consists of daylight and noise contributions only (not illustrated) , and **C–B** is substantially proportional (after correcting for the inverse square law) to the distance of the object **99**, where **C** is an offset value.

While Figures 5a and 5b illustrate the principle of the invention in relation to a single pulse emitted in the time window **10**, it shall be understood that the illustrated pulse is part of a sequence of pulses as defined above. Figure 5c schematically illustrates exemplary timing characteristics of such a sequence. As illustrated, the illumination scheme **40** consists of a repeated emission of a sequence **30** of individual pulses **10**. The width of the individual pulses **10** is determined by the maximal operating range. The entire sequence may be repeated at a frequency of, for example, 60 Hz.

Reflections of light by objects at a short distances are more likely to cause pixel saturation, because the attenuation of such a reflection will be much less than that of a reflection originating from a more distant object (due to the inverse-square law of light attenuation over distance) . As certain applications, such as automotive applications, require accurate system operation up to relatively long distances, a large photon span must be covered between the nearest distances of operation and the farthest distances of operation. With these constraints, pixel saturation at short range is a very real risk, in particular at the first well (which receives the bulk of the reflection at short range) . The inventors have found that for given total pixel space, the saturation problem can be mitigated by using an asymmetric well arrangement, in which the photon capacity represented by the first well is increased, and the photon capacity represented by the second well is decreased. If the increase and decrease are

balanced, an increase of the dynamic range can be obtained at no additional pixel surface cost .

Blooming is a phenomenon that happens when the charge in a pixel exceeds the saturation level of that specific pixel. Consequently, the charge starts to overflow and causes nuisance in adjacent pixels. This creates inaccurate data in the neighboring pixels. Preferably, the pixels of the system according to the present invention are provided with anti-blooming electronics, to bleed off the excess charge before it saturates the relevant well and spills over to the wells of adjacent pixels. In particular when the information from neighboring spots is used for the elimination of background light, it is of great importance to have an accurate estimation of the background light which is obtained independently (and without contamination from) neighboring pixels.

Embodiments of the present invention may employ correlated double sampling to correct the samples for the thermal noise related to the capacity of the wells (also designated as "kTC noise") . To this end, the electronics of the pixel may be designed to carry out a differential measurement between the reset voltage (V_{reSet}) and the signal voltage (V_{Signal}), for example by measuring V_{reSet} at the beginning of the frame and measuring V_{Signal} at the end of the frame. As an alternative to an electronic (in-pixel) implementation, correlated double sampling may also be implemented by digitally subtracting the read-out signals ($V_{Signal} - V_{reSet}$) in a processor .

To increase the amount of light that reaches the photosensitive elements (in particular diodes) in the pixel structure, embodiments of the present invention may use backside illumination; in that case, the pixel circuitry is behind the photosensitive layer, thus reducing the number of layers that must be traversed by the impinging photons to read the photosensitive elements .

The ranging system according to the present invention may be integrated with a triangulation-based system in accordance with WO 2015/004213 A1. If miniaturization is aimed for, the triangulation-based system will end up having a relatively small distance between its projector and its detector, thus leaving it with a reduced operating range. However, it is precisely at short range that the combination presents its benefit, because the triangulation-based system can cover the distances at which the time-of-flight based system cannot operate sufficiently accurately.

The entire ranging process may be repeated iteratively, so as to monitor the distance to the detected object or objects over time. Thus, the result of this method can be used in processes that require information about the distance to detected objects on a continuous basis, such as advanced driver assistance systems, vehicles with an active suspension, or autonomous vehicles.

In order for all elements of the system as described to operate optimally, the system has to be thermally stable. Thermal stability avoids, among other things, undesired wavelength shifts of the optical elements (thermal drift), which would otherwise impair the proper functioning of the optical filters and other elements of the optical chain. Embodiments of the system according to the present invention achieves thermal stability by their design, or by active regulation by means of a temperature control loop with a PID-type controller.

WO 2015/004213 A1 discloses various techniques to minimize the amount of ambient light that reaches the pixels during the detection intervals, thus improving the accuracy of the detection of the patterned laser spots. While these techniques have not been disclosed in the context of a LIDAR system, the inventors of the present invention have found that several such techniques yield excellent results when combined with embodiments of the present invention. This is particularly true for the use of narrow bandpass filters at the detector, and the use of adequate optical

arrangements to ensure nearly perpendicular incidence of the reflected light onto the filters. The details of these arrangements as they appear in WO 2015/004213 A1 are hereby incorporated by reference. Further features and details are provided hereinafter.

While various techniques known from WO 2015/004213 A1 may be applied to embodiments of the present invention to minimize the amount of ambient light that reaches the pixels during the detection intervals, a certain amount of ambient light cannot be avoided. In a multi-pixel system, only some of the pixels will be illuminated by reflected spots, while others will be illuminated by residual ambient light only. The signal levels of the latter group of pixels can be used to estimate the contribution of the ambient light to the signals in the pixels of interest, and to subtract that contribution accordingly. Additionally or alternatively, background light or ambient light may be subtracted from the detected signal at pixel level. This requires two exposures, one during the arrival of the laser pulse and one in the absence of a pulse.

In some embodiments, the detector may be a high dynamic range detector, i.e. a detector having a dynamic range of at least 90 dB, preferably at least 120 dB. The presence of a high dynamic range sensor, i.e. a sensor capable of acquiring a large amount of photons without saturation while maintaining sufficient discrimination of intensity levels in the darkest part of the scene, is an advantage of the use of such a sensor; it allows for a sensor that has a very long range and yet remains capable of detection objects at short distance (where the reflected light is relatively intense) without undergoing saturation. The inventors have found that the use of a true high dynamic range sensor is more advantageous than the use of a sensor that applies tone mapping. In tone mapping, the sensor linear range is compressed towards the higher resolution. In literature, several compression methods are documented, such as logarithmic compression or multilinear compression (see Figure 4). However, this non-linear

compression necessitates relinearisation of the signals before performing logical or arithmetic operations on the captured scene to extract the relief information. The solution according to the invention therefore increases detection accuracy without increasing the computational requirements. It is a further advantage of some embodiments to use a fully linear high dynamic range sensor. A pixel architecture and an optical detector that are capable of providing the desired dynamic range characteristics are disclosed in US patent application publication no. US 2014/353472 A1, in particular paragraphs 65-73 and 88, the content of which is incorporated by reference for the purpose of allowing the skilled person to practice this aspect of the present invention .

Embodiments of the present invention use a high dynamic range pixel. This can be obtained by a sizeable full-well capacity of the charge reservoir or by designs limiting the electronic noise per pixel or by usage of CCD gates that do not add noise at charge transfer, or through a design with a large detection quantum efficiency (DQE) (e.g., in the range of 50% for front illumination or 90% in case of back illumination, also known as back thinning) , or by a special design, or by any combination of the listed improvements. Furthermore, the dynamic range can be further enlarged by adding an overflow capacity to the pixel in overlay at its front side (this implementation requires back thinning) . Preferably, the pixel design implements an anti-blooming mechanism.

European patent application no. EP15191288.8 in the name of the present applicant, which has not been published at the filing date of the present application, describes further aspects of a system and method for determining a distance to an object, which may be combined with the present disclosure.

In embodiments of the present invention, e.g. where active suspension vehicle applications are envisaged, the projection of

the spot pattern is advantageously directed downwards, i.e. towards the road.

A system according to the invention may include an implementation of steps of the methods described above in dedicated hardware (e.g., ASIC), configurable hardware (e.g., FPGA), programmable components (e.g., a DSP or general purpose processor with appropriate software), or any combination thereof. The same component(s) may also include other functions. The present invention also pertains to a computer program product comprising code means implementing the steps of the methods described above, which product may be provided on a computer-readable medium such as an optical, magnetic, or solid-state carrier.

The present invention also pertains to a vehicle comprising the system described above.

Embodiments of the present invention may be used advantageously in a wide variety of applications, including without limitation automotive applications, industrial applications, gaming applications, and the like, and this both indoor and outdoor, at short or long range. In some applications, different sensors according to embodiments of the present invention may be combined (e.g., daisy-chained) to produce panoramic coverage, preferably over a full circle (360° field of view).

It should be noted that the method, the pixel, and the pixel array according to the present invention may also be used in triangulation-based systems such as the system of WO 2015/004213 A1, and in existing LIDAR systems, to improve the quality of the measurements in the presence of ambient light.

While the invention has been described hereinabove with reference to separate system and method embodiments, this was done for clarifying purposes only. The skilled person will appreciate that features described in connection with the system or the method alone, can also be applied to the method or the system,

respectively, with the same technical effects and advantages. Furthermore, the scope of the invention is not limited to these embodiments, but is defined by the accompanying claims.

Claims

1. A method for subtracting background light from an exposure value of a first pixel in an imaging array, said first pixel receiving a reflection of a spot from a scenery illuminated by a periodically pulsed pattern of spots, said periodically pulsed pattern comprising in alternation an illuminated phase and a non-illuminated phase, the method comprising:

- accumulating (110) in said first pixel a charge in proportion to a first quantity of incident light, received in said first pixel while detecting said spot during a predetermined amount of time; and
- decreasing (120) said charge in proportion to a second quantity of incident light received during said predetermined amount of time in absence of said spot.

2. The method according to claim 1, wherein said second quantity of incident light comprises light received in said first pixel during said predetermined amount of time in said non-illuminated phase.

3. The method according to claim 1, wherein said second quantity of incident light comprises light received, during said accumulating, in a second pixel of said pixel array, said second pixel being at a sufficient distance from said first pixel so as not to be illuminated by said spot.

4. A pixel adapted for use as said first pixel in the method according to any of the preceding claims.

5. The pixel according to claim 4, comprising a capacitor (130) for storing said charge, said capacitor (130) having a first side (130a) and a second side (130b), wherein said accumulating (110) comprises transferring charges to said first side (130a), and wherein said decreasing (120) comprises transferring charges to said second side (130b).

6. An imaging array comprising a plurality of pixels according to claim 4 or claim 5.

7. A system (200) for determining a distance to an object comprising:

- a solid-state light source (210) arranged for projecting a pattern of spots of laser light towards said object in a sequence of pulses;
- a detector (220) comprising the imaging array according to claim 6, said detector (220) being configured for detecting light representing said pattern of spots as reflected by said object in synchronization with said sequence of pulses; and
- processing means (240) configured to calculate said distance to said object as a function of exposure values generated by said pixels in response to said detected light;

wherein said pixels (220) are configured to generate said exposure values by accumulating, for each pulse of said sequence, a first amount of electrical charge representative of a first amount of light reflected by said object during a first predetermined time window (10) and a second electrical charge representative of a second amount of light reflected by said object during a second predetermined time window (20), said second predetermined time window (20) occurring after said first predetermined time window (10).

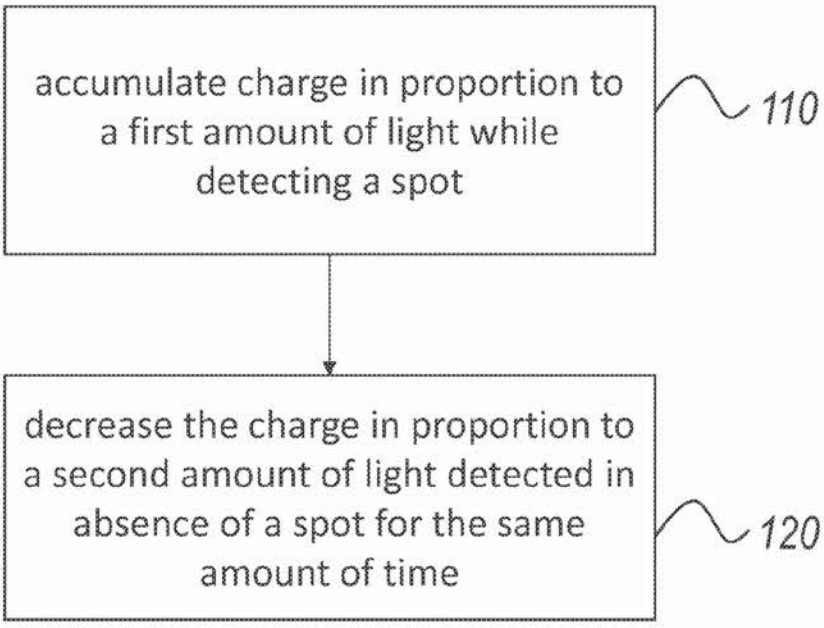

accumulate charge in proportion to a first amount of light while detecting a spot
110
decrease the charge in proportion to a second amount of light detected in absence of a spot for the same amount of time
120

Fig. 1

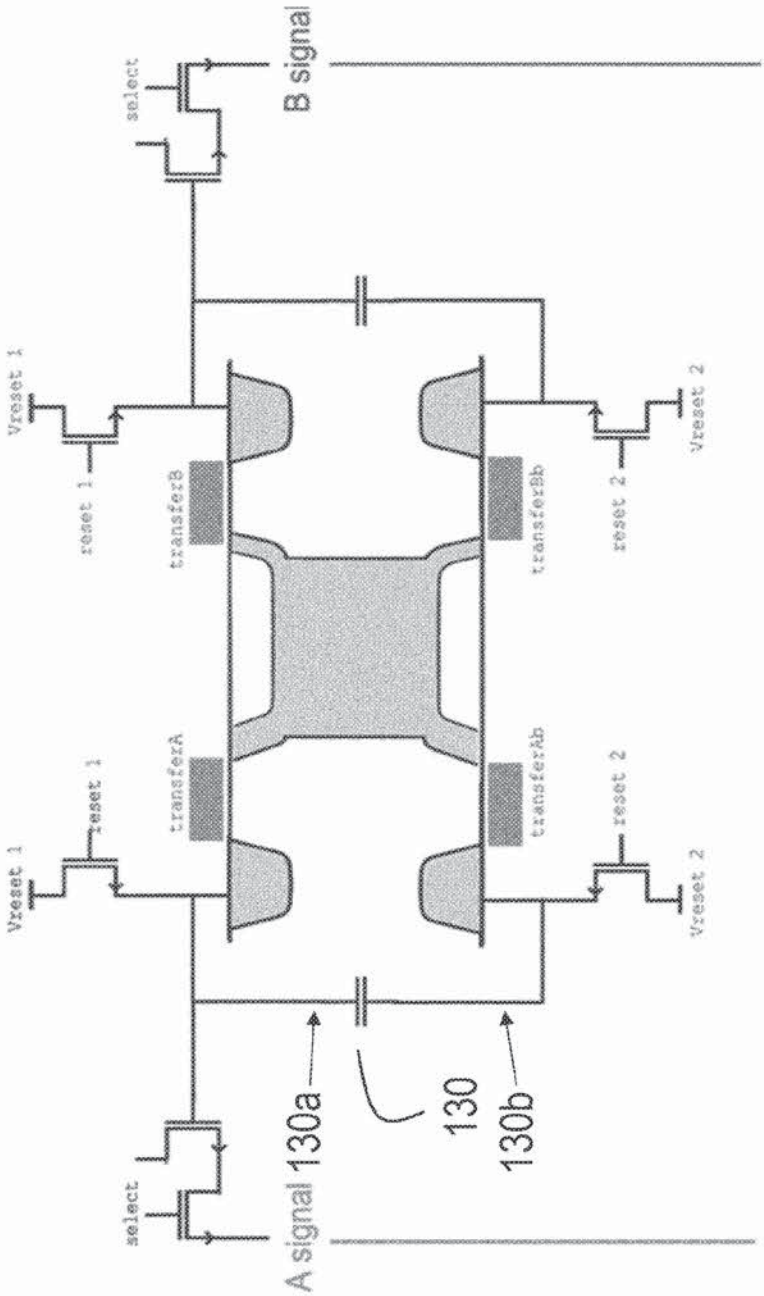

B signal
select
Vreset 1
reset 1
transferB
transferBb
reset 2
Vreset 2
transferA
transferAb
A signal
130a
130
130b

Fig. 2

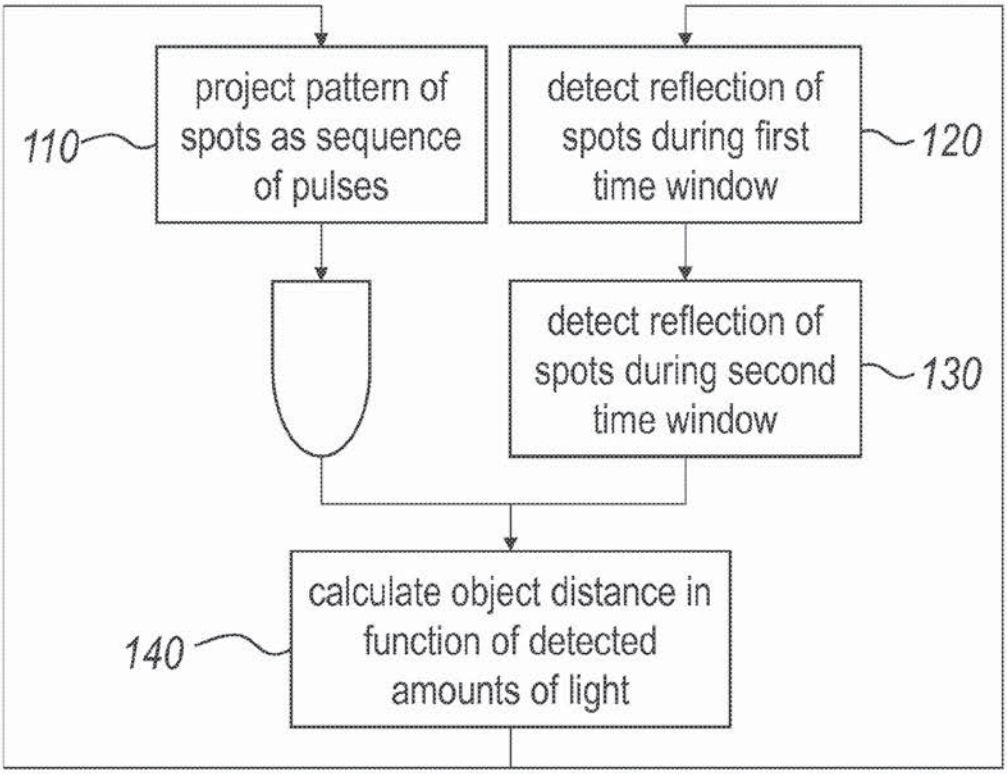

project pattern of spots as sequence of pulses
110
detect reflection of spots during first time window
120
detect reflection of spots during second time window
130
calculate object distance in function of detected amounts of light
140

Fig. 3

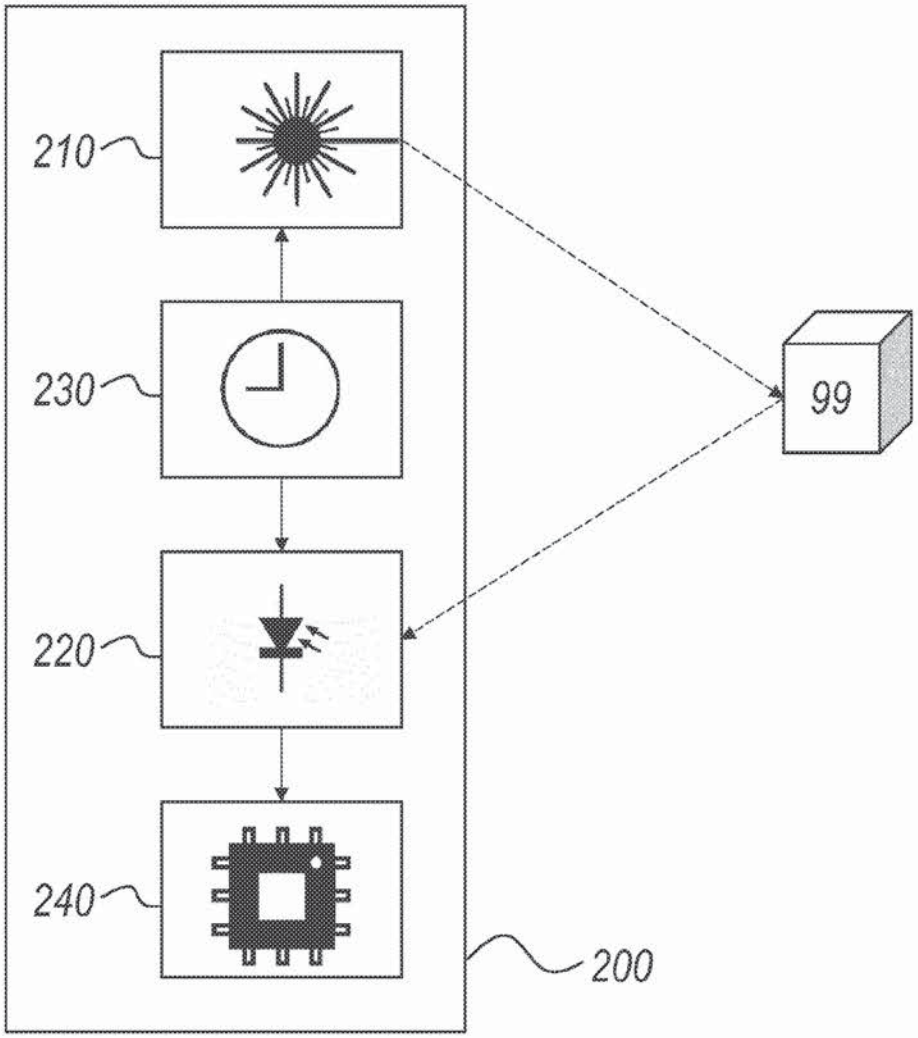


Fig. 4

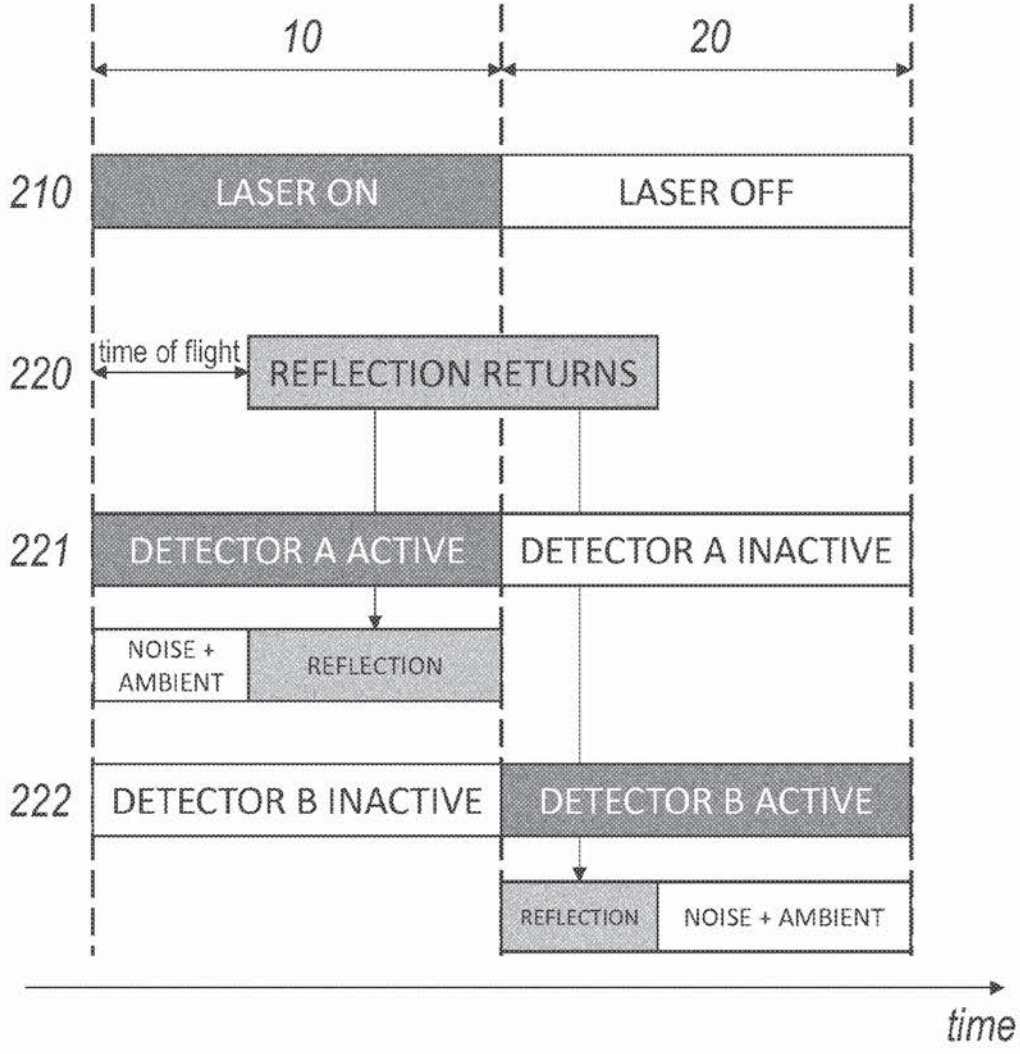

10
20
210
LASER ON
LASER OFF
220
time of flight
REFLECTION RETURNS
221
DETECTOR A ACTIVE
DETECTOR A INACTIVE
NOISE + AMBIENT
REFLECTION
222
DETECTOR B INACTIVE
DETECTOR B ACTIVE
REFLECTION
NOISE + AMBIENT
time

Fig. 5a

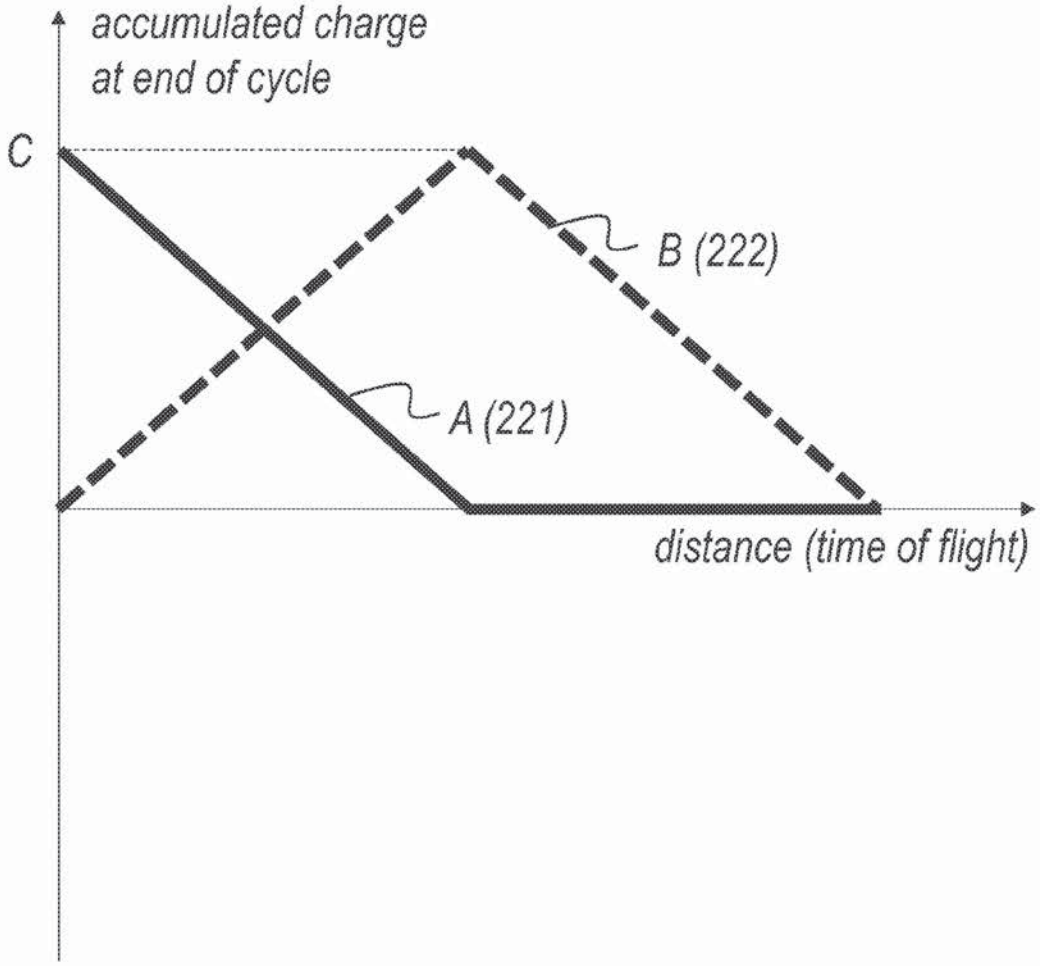

accumulated charge
at end of cycle
C
B (222)
A (221)
distance (time of flight)

Fig. 5b

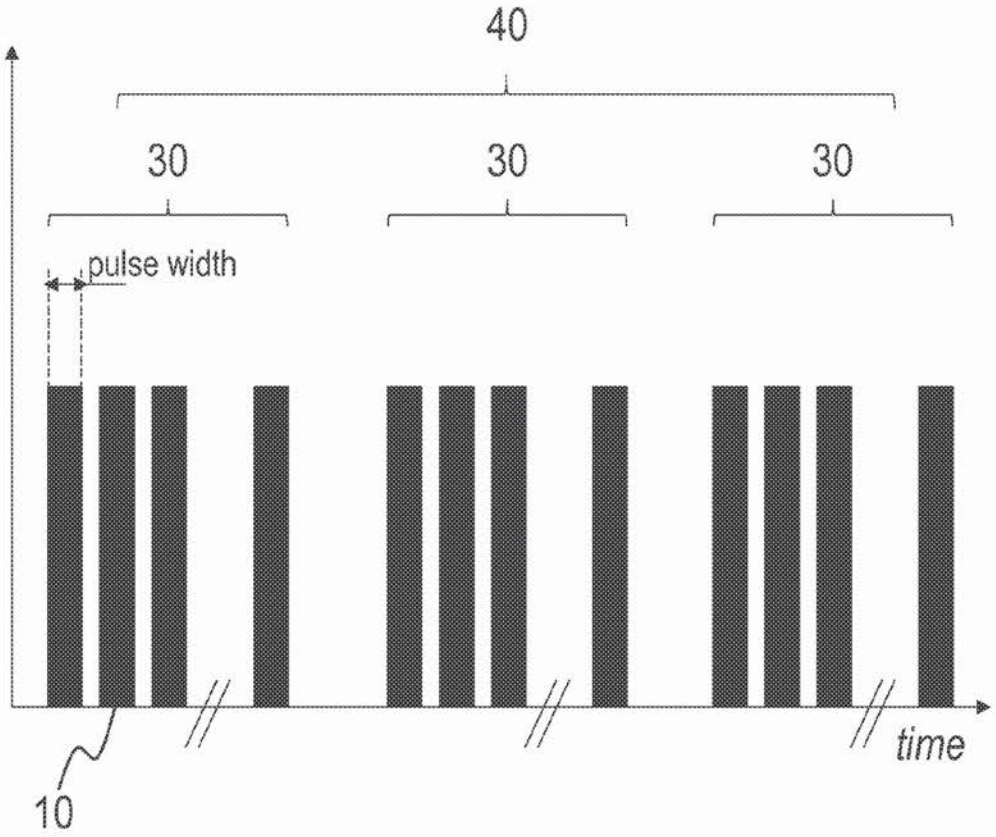


Fig. 5c

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/075093

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S17/10 G01S17/89 G01S7/486 G01S7/487 G01S17/93
G01S7/481
ADD.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01S

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal , INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/008394 A1 (LANGE ROBERT [CH] ET AL) 15 January 2004 (2004-01-15)	1-6
Y	paragraphs [0018], [0030] - [0031], [0043], [0095], [0019], [0086], [0039], [0085], [0025], [0042], [0035], [0060]; figures 8,4	7
Y	US 2013/148102 A1 (OGGIER THIERRY [CH]) 13 June 2013 (2013-06-13)	7
A	paragraphs [0002], [0008], [0014], [0016] - [0028], [0031], [0033], [0035], [0039]; figures 1,5b, 7b, 2	1-6

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" documentwhich may throw doubts on priority claim(s) orwhich is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 2018	06/02/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Metz, Carsten

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2017/075093

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2004008394 A1	15-01-2004	EP 1152261 A1	07-11-2001
		JP 2003532122 A	28-10-2003
		US 2004008394 A1	15-01-2004
		WO 0184182 A1	08-11-2001
US 2013148102 A1	13-06-2013	NONE	

Form PCT/ISA/210 (patent family annex) (April 2005)

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
12 April 2018 (12.04.2018)

W!P O | PCT

(10) International Publication Number
WO 2018/065429 A1

(51) International Patent Classification:
G01S 17/89 (2006.01) *G01S 7/481* (2006.01)
G01S 17/93 (2006.01) *G01S 7/486* (2006.01)
G01S 17/10 (2006.01)

(21) International Application Number:
PCT/EP2017/075096

(22) International Filing Date:
03 October 2017 (03.10.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
16192103.6 03 October 2016 (03.10.2016) EP

(71) Applicant: **XENOMATIX NV** [BE/BE]; Esperantolaan 4, B-3001 Leuven (BE).

(72) Inventors: **VAN DYCK, Dirk;** Kleine Grippe 37, B-2630 Aartselaar (BE). **VAN DEN BOSSCHE, Johan;** Kortrijkstraat 116, B-3210 Linden (BE).

(74) Agent: **IPLODGE BVBA;** Technologielaan 9, B-3001 Heverlee (BE).

(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.

(54) **Title:** SYSTEM AND METHOD FOR DETERMINING A DISTANCE TO AN OBJECT

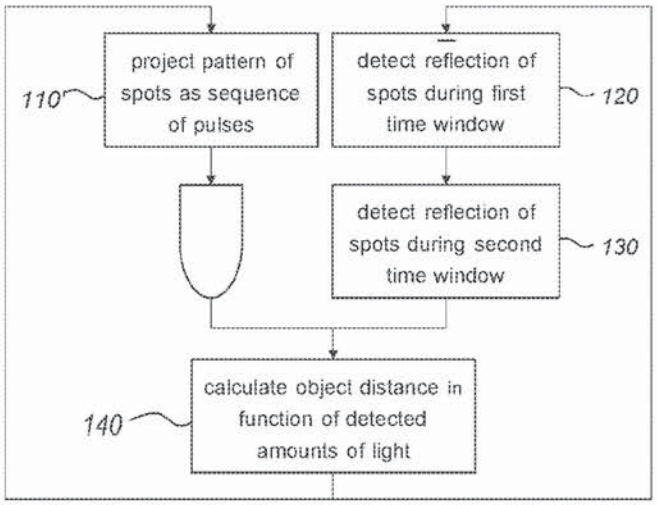


Fig. 1

(57) **Abstract:** The invention pertains to a system for determining a distance, comprising: a light source for projecting a pattern of discrete spots of laser light towards the object in a sequence of pulses; a detector comprising picture elements, for detecting light representing the pattern as reflected by the object in synchronization with the sequence of pulses, and processing means to calculate the distance to the object as a function of exposure values generated by said picture elements. The picture elements generate exposure values by accumulating a first amount of electrical charge representing a first amount of light reflected during a first time window and a second electrical charge representating a second amount of light reflected during a second time window. The system projects and detects for at least two consecutive sequences of pulses, each being operated with a different duration of said first time window and said second time window.

WO 2018/065429 A1

[Continued on nextpage]

(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).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

System and Method for determining a distance to an object

Field of the Invention

The present invention pertains to the field of systems for determining a distance to an object, in particular to time-of-flight based sensing systems to be used for the characterization of a scene or a part thereof.

Background

In the field of remote sensing technology, mainly in the usage of making high-resolution maps of the surroundings, to be used in many control and navigation applications such as but not limited to the automotive and industrial environment, gaming applications, and mapping applications, it is known to use time-of-f light based sensing to determine the distance of objects from a sensor. Time-of-flight based techniques include the use of RF modulated sources, range gated imagers, and direct time-of-f light (DToF) imagers. For the use of RF modulated sources and range gated imagers, it is necessary to illuminate the entire scene of interest with a modulated or pulsed source. Direct time-of-f light systems, such as most LIDARs, mechanically scan the area of interest with a pulsed beam, the reflection of which is sensed with a pulse detector.

In order to be able to correlate an emitted RF modulated signal with the detected reflected signal, the emitted signal must meet a number of constraints. In practice, these constraints turn out to make the RF modulated systems highly impractical for use in vehicular systems: the attainable range of detection is very limited for signal intensities that are within conventional safety limits and within the power budget of regular vehicles.

A direct TOF (DToF) imager, as used in most LIDAR systems, comprises a powerful pulsed laser (operating in a nanosecond pulse regime) , a mechanical scanning system to acquire from the ID point

measurement a 3D map, and a pulse detector. Systems of this type are presently available from vendors including Velodyne Lidar of Morgan Hill, California. The Velodyne HDL-64E, as an example of state-of-the-art systems, uses 64 high-power lasers and 64 detectors (avalanche diodes) in a mechanically rotating structure at 5 to 15 rotations per second. The optical power required by these DToF LIDAR systems is too high to be obtained with semiconductor lasers, whose power is in the range of five to six orders of magnitude lower. In addition, the use of mechanically rotating elements for scanning purposes limits the prospects for miniaturization, reliability, and cost reduction of this type of system.

United States Patent application publication no. 2015/0063387 in the name of Trilumina discloses a VCSEL delivering a total energy of 50 mW in a pulse having a pulse width of 20 ns. The commercially available Optek OPV310 VCSEL delivers a total energy of 60 mW in a pulse having a duration of 10 ns and it can be estimated by extrapolation to have a maximum optical output power of 100 mW. This value is only realized under very stringent operating conditions, meaning optimal duty cycle and short pulse width so as to avoid instability due to thermal problems. Both the Trilumina disclosure and the Optek system illustrate that continuous-wave VCSEL systems are reaching their physical limits with respect to optical peak power output, due to thermal constraints inherently linked to the VCSEL design. At these pulse energy levels, and using ns pulses as presently used in DToF applications, the mere number of photons that can be expected to be usefully reflected by an object at a distance of 120 m is so low that it defeats detection by means of conventional semiconductor sensors such as CMOS or CCD or SPAD array. Thus, increasing the VCSEL power outputs by 5 or 6 orders of magnitude, as would be required to extend the range of the known DToF systems, is physically impossible.

Even the use of avalanche diodes (AD or SPAD), which are theoretically sufficiently sensitive to capture the few returning

photons, cannot be usefully deployed in the known LIDAR system architectures. A solid state implementation of an array of SPADs must be read out serially. A high number of SPADs is required to achieve the desired accuracy. The serial read-out constraints of the solid state implementation limit the bandwidth of the system turning it inappropriate for the desired accuracy. For accuracies such as that of the Velodyne system (0.02 m to 0.04 m, independent of distance), the required read-out data rate exceeds the practically achievable bandwidth in case of today's IC implementation. For operation at 120 m, a SPAD array of 500x500 pixels is required, which, in an IC-based implementation, must be read-out serially. For the same precision as the aforementioned Velodyne system, it would require 1000 pulses per millisecond and hence 1000 frames per millisecond, translating into a readout rate of 250 Gigapixels per second. This is believed to be technically unfeasible in the context of current SPAD IC technology.

The paper by Neil E. Newman et al., "High Peak Power VCSELs in Short Range LIDAR Applications", *Journal of Undergraduate Research in Physics*, 2013, http://www.jurp.org/2 013/12 017EXR.pdf, describes a VCSEL-based LIDAR application. The paper states that the maximum output power of the described prototype system was not great enough to do wide-field LIDAR at a range greater than 0.75 m. With a relatively focused beam (0.02 m spot size at 1 m distance), the authors were able to range a target object at a distance of up to 1 m.

The above examples clearly indicate that the optical power emitted by present semiconductor lasers cannot meet the power requirements necessary for operations in the known LIDAR systems to be of practical use in automotive applications (e.g. for ranges up to 120 m).

United States patent no. 7,544,945 in the name of Avago Technologies General IP (Singapore) Pte. Ltd., discloses vehicle-based LIDAR systems and methods using multiple lasers to provide more compact and cost-effective LIDAR functionality. Each laser in

an array of lasers can be sequentially activated so that a corresponding optical element mounted with respect to the array of lasers produces respective interrogation beams in substantially different directions. Light from these beams is reflected by objects in a vehicle's environment, and detected so as to provide information about the objects to vehicle operators and/or passengers. The patent provides a solid state projector in which the individual lasers are consecutively activated in order to replace the known mechanical scanning in the known DToF LIDAR systems.

A high-accuracy medium-range surround sensing system for vehicles that does not use time-of-flight detection, is known from international patent application publication WO 2015/004213 A1 in the name of the present applicant. In that publication, the localization of objects is based on the projection of pulsed radiation spots and the analysis of the displacement of detected spots with reference to predetermined reference spot positions. More in particular, the system of the cited publication uses triangulation . However, the accuracy that can be achieved correlates with the triangulation base, which limits the further miniaturization that can be achieved.

US patent application publication no. US 2012/0038903 A1 discloses methods and systems for adaptively controlling the illumination of a scene. In particular, a scene is illuminated, and light reflected from the scene is detected. Information regarding levels of light intensity received by different pixels of a multiple pixel detector, corresponding to different areas within a scene, and/or information regarding a range to an area within a scene, is received. That information is then used as a feedback signal to control levels of illumination within the scene. More particularly, different areas of the scene can be provided with different levels of illumination in response to the feedback signal.

European patent application publication no. EP 2 322 953 A1 discloses a distance image sensor capable of enlarging the distance measurement range without reducing the distance resolution. A radiation source provides first to fifth pulse trains which are irradiated to the object as radiation pulses in the first to fifth frames arranged in order on a time axis. In each of the frames, imaging times are prescribed at points of predetermined time from the start point of each frame, also the pulses are shifted respectively by shift amounts different from each other from the start point of the first to fifth frames. A pixel array generates element image signals each of which has distance information of an object in distance ranges different from each other using imaging windows A and B in each of five frames. A processing unit generates an image signal by combining the element image signals. Since five times-of-f light measurement are used, the width of the radiation pulse does not have to be increased to obtain distance information of the object in a wide distance range, and the distance resolution is not reduced.

European patent application publication no. EP 2 290 402 A1 discloses a range image sensor which is provided on a semiconductor substrate with an imaging region composed of a plurality of two-dimensionally arranged units, thereby obtaining a range image on the basis of charge quantities output from the units. One of the units is provided with a charge generating region (region outside a transfer electrode) where charges are generated in response to incident light, at least two semiconductor regions which are arranged spatially apart to collect charges from the charge generating region, and a transfer electrode which is installed at each periphery of the semiconductor region, given a charge transfer signal different in phase, and surrounding the semiconductor region.

The article by Shoji Kawahito et al., "A CMOS Time-of-Flight Range Image Sensor With Gates-on-Field-Oxide Structure", *IEEE Sensors Journal*, Vol. 7, no. 12, p. 1578-1586, discloses a type of CMOS time-of-flight (TOS) range image sensor using single-layer gates

on field oxide structure for photo conversion and charge transfer. This structure allows the realization of a dense TOF range imaging array with 15 x 15 μm^2 pixels in a standard CMOS process. Only an additional process step to create an n-type buried layer which is necessary for high-speed charge transfer is added to the fabrication process. The sensor operates based on time-delay dependent modulation of photocharge induced by back reflected infrared light pulses from an active illumination light source. To reduce the influence of background light, a small duty cycle light pulse is used and charge draining structures are included in the pixel. The TOF sensor chip fabricated measures a range resolution of 2.35 cm at 30 frames per second an improvement to 0.74 cm at three frames per second with a pulse width of 100 ns.

European patent application no. EP15191288.8 in the name of the present applicant, which has not been published at the filing date of the present application, describes some aspects of a system and method for determining a distance to an object.

There is a continuing need to obtain extreme miniaturization and/or longer-range in complex vehicular surround sensing applications, such as ADAS (autonomous driving assistance system) applications and autonomous driving applications, and this at a reasonable cost and in a compact, semiconductor-integrated form factor .

Summary of the Invention

It is an objective of embodiments of the present invention to provide a further miniaturized and longer-range alternative for displacement-based vehicular surround sensing systems. Furthermore, it is an objective of embodiments of the present invention to provide a full solid-state alternative for the known LIDAR systems.

According to an aspect of the present invention, there is provided a system for determining a distance to an object comprising: a

solid-state light source arranged for projecting a pattern of discrete spots of laser light towards the object in a sequence of pulses; a detector comprising a plurality of picture elements, the detector being configured for detecting light representing the pattern of discrete spots as reflected by the object in synchronization with the sequence of pulses; and processing means configured to calculate the distance to the object as a function of exposure values generated by the picture elements in response to the detected light; wherein the picture elements are configured to generate the exposure values by accumulating, for all of the pulses of the sequence, a first amount of electrical charge representative of a first amount of light reflected by the object during a first predetermined time window and a second electrical charge representative of a second amount of light reflected by the object during a second predetermined time window, the second predetermined time window occurring after the first predetermined time window; wherein the system is configured to perform the projecting and the detecting for at least two consecutive sequences of pulses, each of the sequences being operated with a different duration of the first predetermined time window and the second predetermined time window.

The present invention relies on the same physical principles as direct time-of-f light based ranging systems, viz. the fact that light always takes a certain amount of time to travel a given distance. However, the present invention uses range gating to determine the distance travelled by a light pulse that has been transmitted and subsequently reflected by a target object. The present invention is *inter alia* based on the insight of the inventors that by combining range gating, an at least partially simultaneous spot pattern projection (based on a novel illumination scheme) and a low-power semiconductor light source, a substantially miniaturized, full solid state and energy-efficient long-range distance detection method can be obtained. The term "pattern" as used herein refers to a spatial distribution of simultaneously projected spots. In order to determine the position of the detected spot reflection in three-dimensional space, it is