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(54) **LIDAR SYSTEM WITH IMPROVED SCANNING SPEED FOR HIGH-RESOLUTION DEPTH MAPPING**

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(51) **Int. Cl.**

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G01S 7/481	(2006.01)
G01S 17/10	(2006.01)

(52) **U.S. Cl.**

CPC ***G01S 7/4817*** (2013.01); ***G01S 7/4812*** (2013.01); ***G01S 7/4816*** (2013.01); ***G01S 17/10*** (2013.01)

(58) **Field of Classification Search**

CPC G01S 7/4817; G01S 7/4812; G01S 17/10
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,006,721	A	4/1991	Cameron et al.
5,198,657	A	3/1993	Trost et al.
5,696,778	A	2/1997	MacPherson

(Continued)

FOREIGN PATENT DOCUMENTS

WO	WO 2017/079483	5/2017
WO	WO 2017/095817	6/2017

OTHER PUBLICATIONS

U.S. Appl. No. 15/180,580, filed Jun. 13, 2016, Hall.

(Continued)

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(57) **ABSTRACT**

A lidar system may have a light source configured to emit a pulse of light and a scanner that scans a field of view of the light source in a forward-scanning direction across a plurality of pixels located downrange from the lidar system. The scanner can direct the pulse of light toward the second pixel and scan a field of view of a first detector. The first-detector field of view can be offset from the light-source field of view in a direction opposite the forward-scanning direction. When the pulse is emitted, the first-detector field of view can at least partially overlap the first pixel and the light-source field of view can at least partially overlap the second pixel. The first detector can be configured to detect a portion of the pulse of light scattered by a target located at least partially within the second pixel.

20 Claims, 8 Drawing Sheets

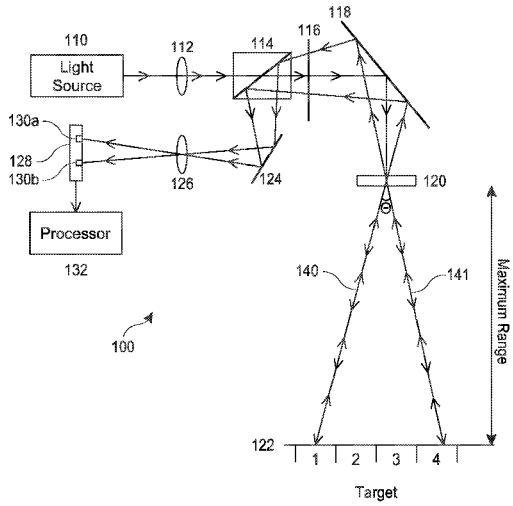

Exhibit 1043
Hesai v. Ouster
IPR2023-01457

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,867,305 A 2/1999 Waarts et al.
5,872,621 A 2/1999 Wilkerson et al.
5,892,575 A 4/1999 Marino
6,449,384 B2 9/2002 Laumeyer et al.
6,710,324 B2 3/2004 Hipp
6,723,975 B2 4/2004 Saccomanno
6,747,747 B2 6/2004 Hipp
6,759,649 B2 7/2004 Hipp
7,092,548 B2 8/2006 Laumeyer et al.
7,209,221 B2 4/2007 Breed et al.
7,345,271 B2 3/2008 Boehlau et al.
7,433,903 B1 10/2008 Shapiro et al.
7,443,903 B2 10/2008 Leonardo et al.
7,532,311 B2 5/2009 Henderson et al.
7,570,793 B2 8/2009 Lages et al.
7,583,364 B1 9/2009 Mayor et al.
7,649,920 B2 1/2010 Welford
7,652,752 B2 1/2010 Fetzer et al.
7,872,794 B1 1/2011 Minelly et al.
7,902,570 B2 3/2011 Itzler et al.
7,945,408 B2 5/2011 Dimsdale et al.
7,969,558 B2 6/2011 Hall
7,995,796 B2 8/2011 Retterath et al.
8,059,263 B2 11/2011 Haberer et al.
8,072,663 B2 12/2011 O'Neill et al.
8,081,301 B2 12/2011 Stann et al.
8,138,849 B2 3/2012 West et al.
8,279,420 B2 10/2012 Ludwig et al.
8,280,623 B2 10/2012 Trepagnier et al.
8,346,480 B2 1/2013 Trepagnier et al.
8,364,334 B2 1/2013 Au et al.
8,452,561 B2 5/2013 Dimsdale et al.
8,541,744 B1 9/2013 Liu
8,548,014 B2 10/2013 Fermann et al.
8,625,080 B2 1/2014 Heizmann et al.
8,675,181 B2 3/2014 Hall
8,723,955 B2 5/2014 Kiehn et al.
8,767,190 B2 7/2014 Hall
8,796,604 B2 8/2014 Lynass et al.
8,804,787 B1 8/2014 Coleman et al.
8,817,096 B1 8/2014 Ni et al.
8,836,922 B1 9/2014 Pennecot et al.
8,880,296 B2 11/2014 Breed
8,896,818 B2 11/2014 Walsh et al.
8,934,509 B2 1/2015 Savage-Leuchs et al.
9,000,347 B2 4/2015 Woodward et al.
9,041,136 B2 5/2015 Chia
9,048,370 B1 6/2015 Urmson et al.
9,063,549 B1 6/2015 Pennecot et al.
9,069,060 B1 6/2015 Zbrozek et al.
9,074,878 B2 7/2015 Steffey et al.
9,086,273 B1 7/2015 Gruver et al.
9,086,481 B1 7/2015 Dowdall et al.
9,091,754 B2 7/2015 D'Aligny
9,103,669 B2 8/2015 Giacotto et al.
9,121,703 B1 9/2015 Droz et al.
9,160,140 B2 10/2015 Gusev et al.
9,170,333 B2 10/2015 Mheen et al.
9,199,641 B2 12/2015 Ferguson et al.
9,213,085 B2 12/2015 Kanter
9,239,260 B2 1/2016 Bayha et al.
9,246,041 B1 1/2016 Clausen et al.
9,285,464 B2 3/2016 Pennecot et al.
9,285,477 B1 3/2016 Smith et al.
9,297,901 B2 3/2016 Bayha et al.
9,299,731 B1 3/2016 Lenius et al.
9,304,154 B1 4/2016 Droz et al.
9,304,203 B1 4/2016 Droz et al.
9,304,316 B2 4/2016 Weiss et al.
9,310,471 B2 4/2016 Sayyah et al.
9,335,255 B2 5/2016 Retterath et al.
9,360,554 B2 6/2016 Retterath et al.
9,368,933 B1 6/2016 Nijjar et al.
9,383,201 B2 7/2016 Jachman et al.
9,383,445 B2 7/2016 Lu et al.
9,383,753 B1 7/2016 Templeton et al.
2002/0041435 A1 4/2002 Krummrich
2002/0060784 A1 5/2002 Pack et al.
2003/0043058 A1 3/2003 Jamieson et al.
2005/0214690 A1 9/2005 Verheijden et al.
2006/0227316 A1 10/2006 Gatt
2006/0231771 A1 10/2006 Lee et al.
2006/0290920 A1 12/2006 Kämpchen et al.
2007/0040121 A1 2/2007 Kalayeh
2007/0182949 A1 8/2007 Niclass
2007/0247612 A1 10/2007 Pack et al.
2008/0027591 A1 1/2008 Lenser et al.
2008/0074640 A1 3/2008 Walsh et al.
2008/0181266 A1 7/2008 Deladurantaye et al.
2008/0309913 A1 12/2008 Fallon
2009/0122295 A1 5/2009 Eaton
2009/0262760 A1 10/2009 Krupkin et al.
2009/0273770 A1 11/2009 Bauhahn et al.
2010/0034221 A1 2/2010 Dragic
2010/0091263 A1 4/2010 Kumagai et al.
2010/0128744 A1 5/2010 Deladurantaye et al.
2011/0085149 A1 4/2011 Nathan
2011/0122012 A1 5/2011 Van Zeijl et al.
2012/0038903 A1 2/2012 Weimer et al.
2012/0168605 A1 7/2012 Milanovic
2012/0206712 A1 8/2012 Chang et al.
2012/0227263 A1 9/2012 Leclair et al.
2012/0268105 A1 10/2012 Mann et al.
2013/0010820 A1 1/2013 Curtis
2013/0033742 A1 2/2013 Rogers et al.
2013/0282208 A1 10/2013 Mendez-Rodriguez et al.
2014/0111805 A1 4/2014 Albert et al.
2014/0146303 A1 5/2014 Mitchell et al.
2014/0168631 A1 6/2014 Haslim et al.
2014/0176933 A1 6/2014 Haslim et al.
2014/0211194 A1 7/2014 Pacala et al.
2014/0268098 A1 9/2014 Schwartz
2014/0268311 A1 9/2014 Zhu
2014/0293263 A1 10/2014 Justice et al.
2014/0293266 A1 10/2014 Hsu et al.
2014/0330479 A1 11/2014 Dolgov
2014/0376001 A1 12/2014 Swanson
2015/0109605 A1 4/2015 Major, Jr. et al.
2015/0131080 A1 5/2015 Retterath et al.
2015/0177368 A1 6/2015 Bayha et al.
2015/0185244 A1 7/2015 Inoue et al.
2015/0185313 A1 7/2015 Zhu
2015/0192676 A1 7/2015 Kotelnikov et al.
2015/0192677 A1 7/2015 Yu et al.
2015/0204978 A1 7/2015 Hammes et al.
2015/0214690 A1 7/2015 Savage-Leuchs et al.
2015/0219765 A1 8/2015 Mead et al.
2015/0301182 A1 10/2015 Geiger et al.
2015/0316415 A1 11/2015 Islam
2015/0323654 A1 11/2015 Jachmann et al.
2015/0378023 A1 12/2015 Royo et al.
2015/0378241 A1 12/2015 Eldada
2016/0025842 A1 1/2016 Anderson et al.
2016/0041266 A1* 2/2016 Smits G01S 17/66 356/5.01
2016/0047896 A1 2/2016 Dussan
2016/0047901 A1 2/2016 Pacala et al.
2016/0049765 A1 2/2016 Eldada
2016/0146939 A1 5/2016 Shpunt et al.
2016/0146940 A1 5/2016 Koehler
2016/0161600 A1 6/2016 Eldada et al.
2016/0245919 A1 8/2016 Kalscheur et al.
2017/0131388 A1 5/2017 Campbell et al.

OTHER PUBLICATIONS

Search Report and Written Opinion mailed Feb. 1, 2017 in corresponding PCT Application No. PCT/US16/60397, 9 pgs.
Search Report and Written Opinion in corresponding PCT Application No. PCT/US2016/064020 dated Apr. 4, 2017, 37 pgs.
Office Action dated Jul. 13, 2017 in U.S. Appl. No. 15/470,718, 17 pgs.

(56) **References Cited**

OTHER PUBLICATIONS

Office Action dated Aug. 14, 2017 in U.S. Appl. No. 15/470,708, 15 pgs.

* cited by examiner

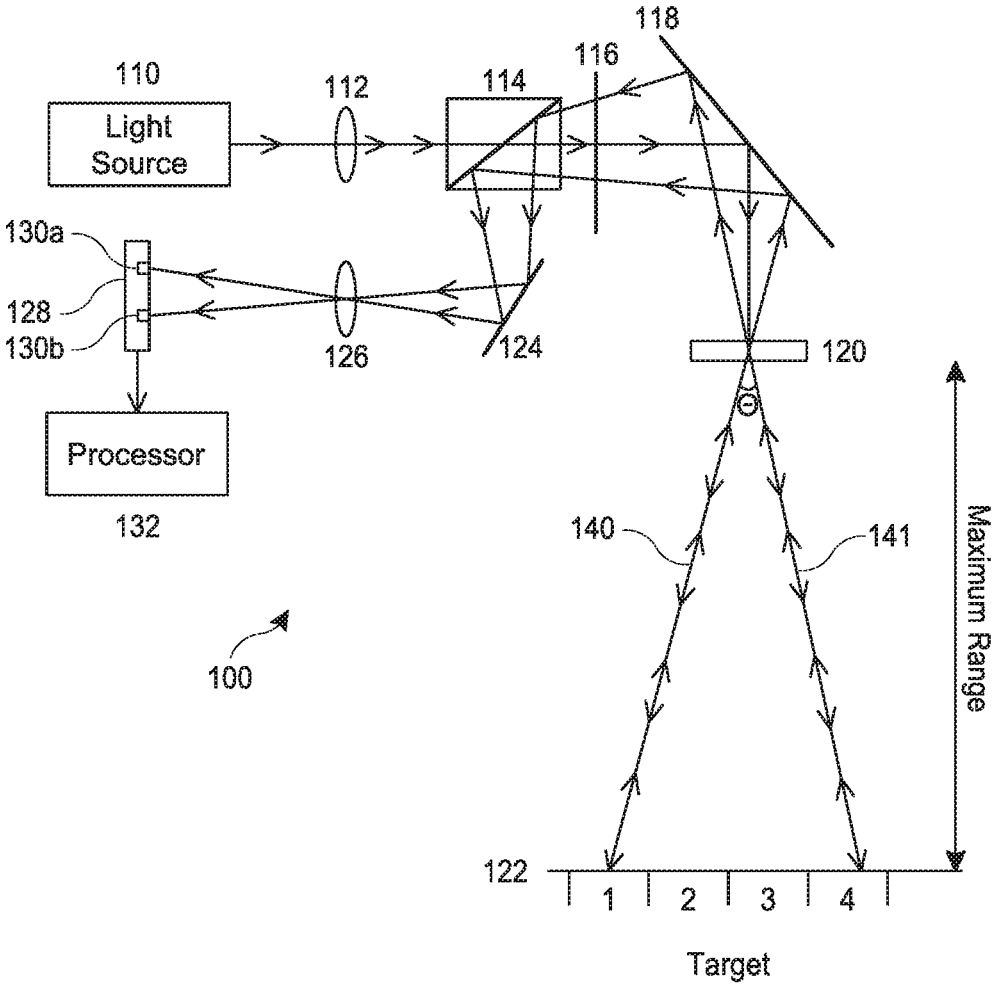
118
116
110
112
114
Light Source
130a
128
130b
126
124
120
Processor
132
140
141
Maximum Range
100
122
1
2
3
4
Target

FIG. 1

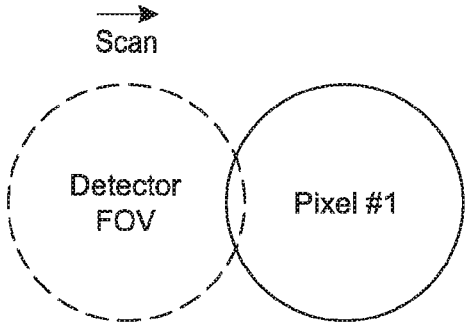

FIG. 2

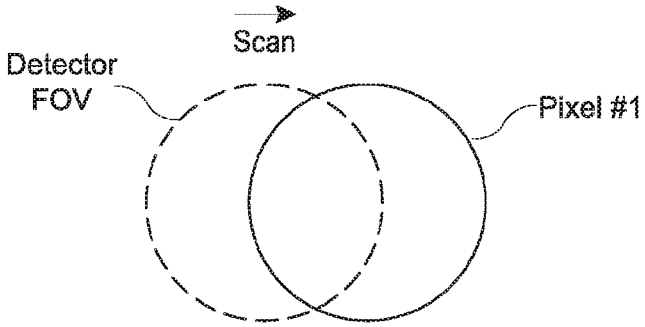

FIG. 3

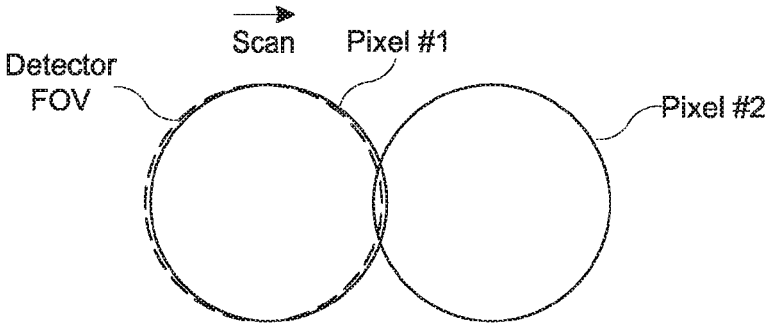

FIG. 4

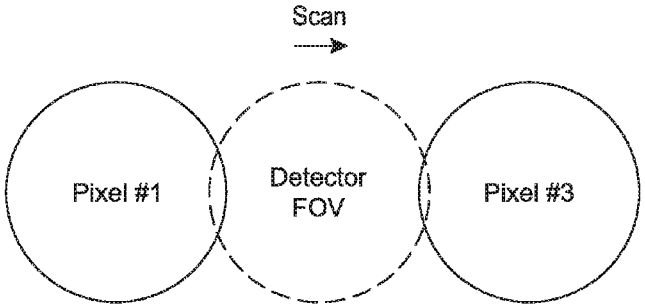

FIG. 5

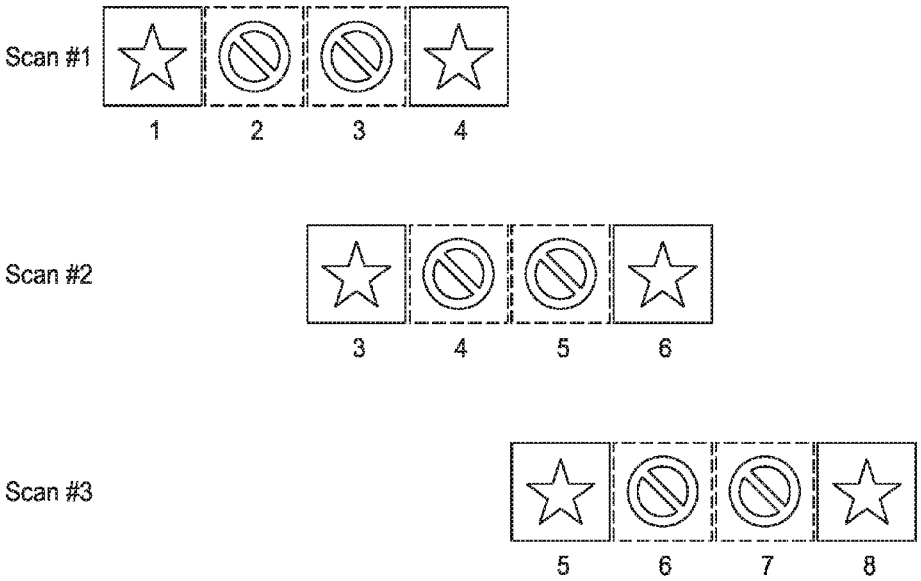

FIG. 6

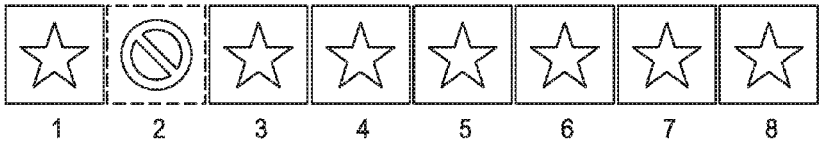

FIG. 7

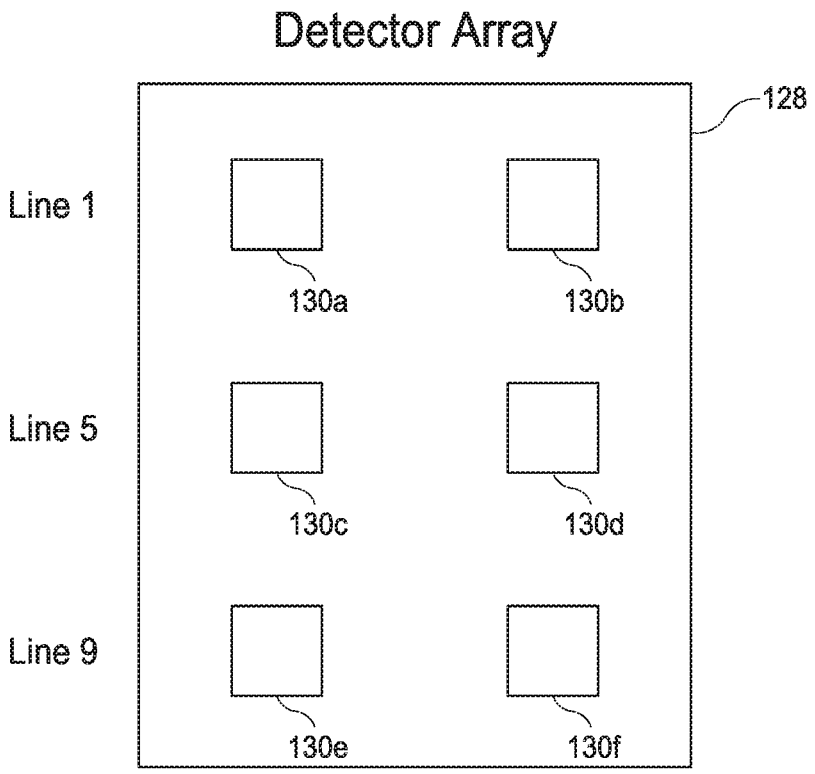
Detector Array
128
Line 1
130a
130b
Line 5
130c
130d
Line 9
130e
130f

FIG. 8

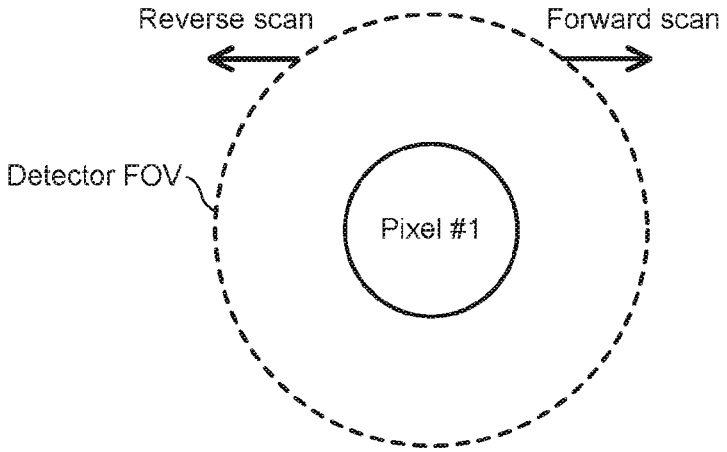

FIG. 9

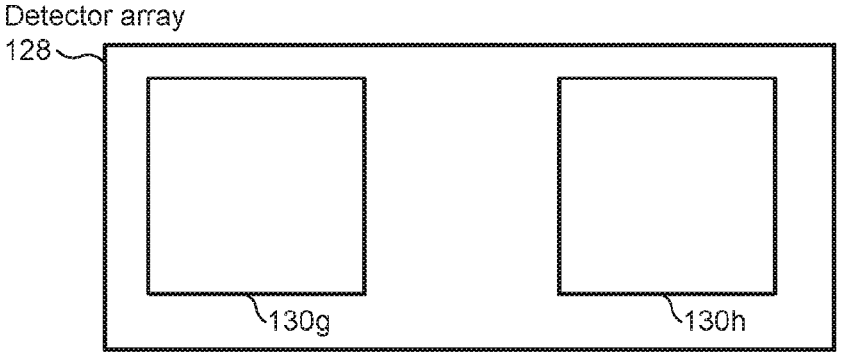

FIG. 10

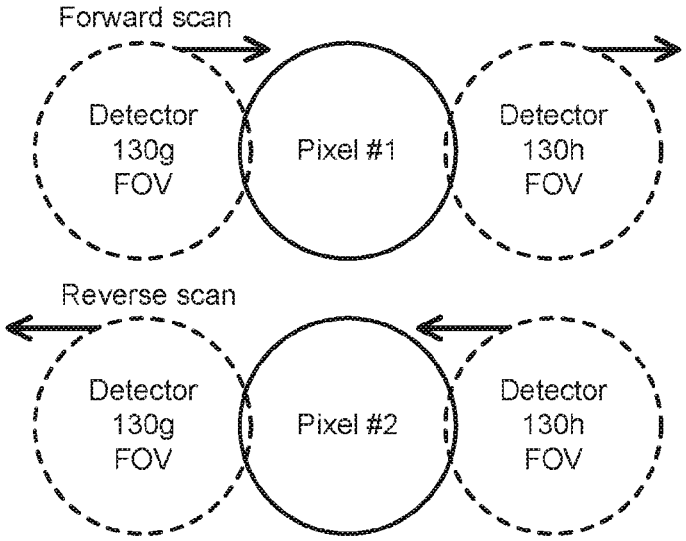

FIG. 11

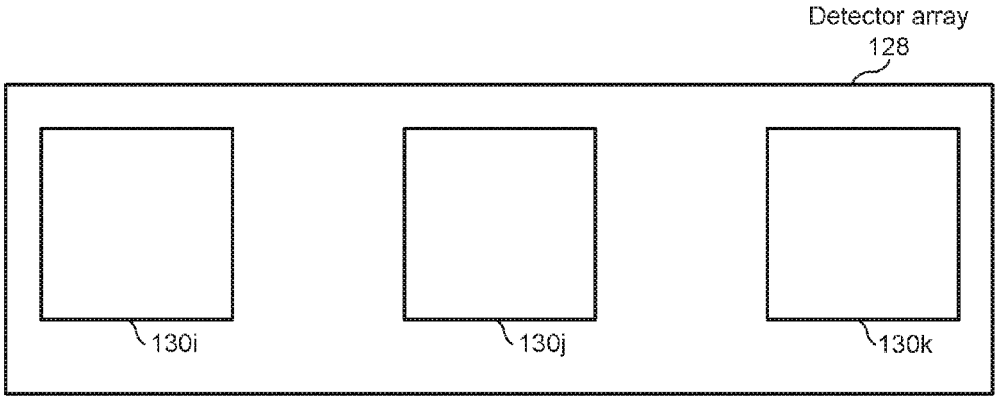
Detector array
128
130i
130j
130k

FIG. 12

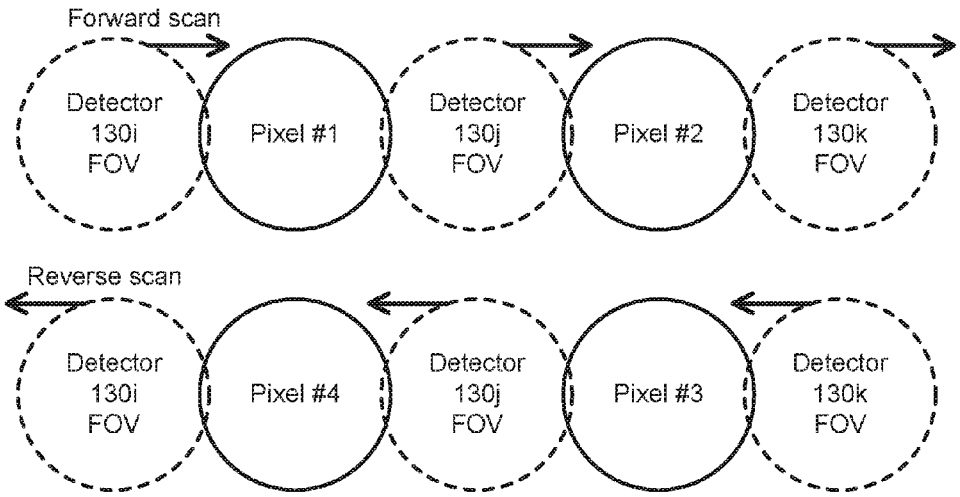
Forward scan
Detector
130i
FOV
Pixel #1
Detector
130j
FOV
Pixel #2
Detector
130k
FOV
Reverse scan
Detector
130i
FOV
Pixel #4
Detector
130j
FOV
Pixel #3
Detector
130k
FOV

FIG. 13

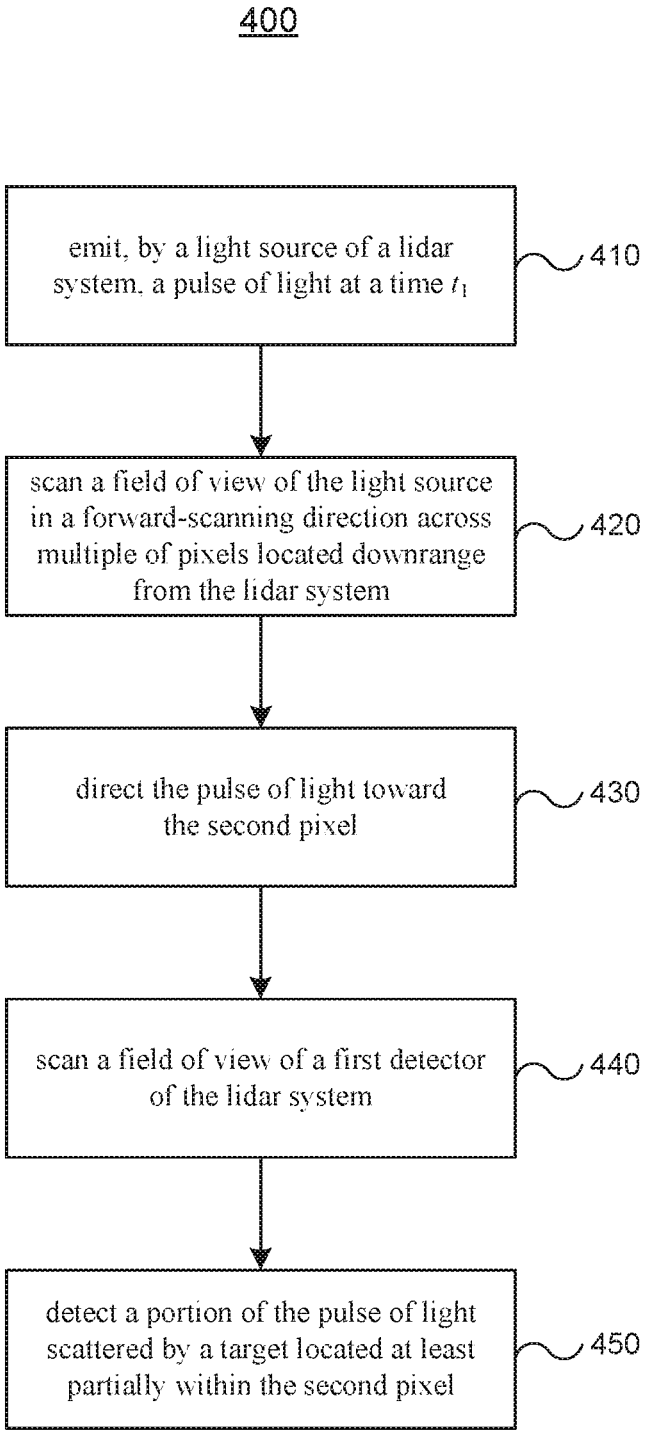
400
emit, by a light source of a lidar system, a pulse of light at a time t_1
410
scan a field of view of the light source in a forward-scanning direction across multiple of pixels located downrange from the lidar system
420
direct the pulse of light toward the second pixel
430
scan a field of view of a first detector of the lidar system
440
detect a portion of the pulse of light scattered by a target located at least partially within the second pixel
450

FIG. 14

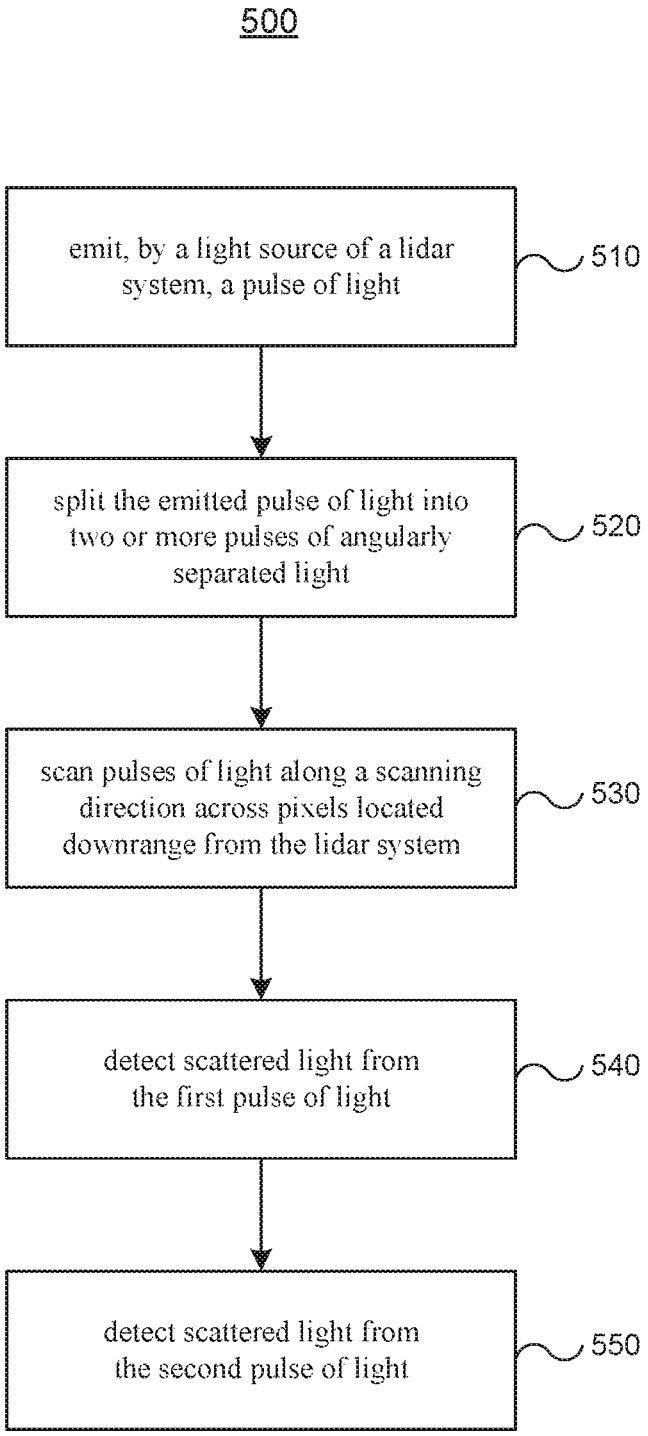
500
emit, by a light source of a lidar system, a pulse of light
510
split the emitted pulse of light into two or more pulses of angularly separated light
520
scan pulses of light along a scanning direction across pixels located downrange from the lidar system
530
detect scattered light from the first pulse of light
540
detect scattered light from the second pulse of light
550

FIG. 15

LIDAR SYSTEM WITH IMPROVED SCANNING SPEED FOR HIGH-RESOLUTION DEPTH MAPPING

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

Any and all applications for which a foreign or domestic priority claim is identified in the Application Data Sheet as filed with the present application are hereby incorporated by reference under 37 CFR 1.57. For example, this application claims priority to U.S. Provisional Patent Application No. 62/251,672, filed Nov. 5, 2015, and entitled "LIDAR SYSTEM WITH IMPROVED SCANNING SPEED FOR HIGH-RESOLUTION DEPTH MAPPING," the entirety of which is hereby incorporated by reference herein.

BACKGROUND OF THE INVENTION

Field of the Invention

This disclosure relates to scanning lidar systems for creating a depth map of a field of regard.

Description of the Related Art

Lidar is a technology that can be used to measure distances to remote targets. Typically, a lidar system includes a light source and a detector. The light source emits light pulses toward a target which then scatters the light. Some of the scattered light is received back at the detector. The system determines the distance to the target based on one or more characteristics associated with the returned light pulses. For example, the system may determine the distance to the target based on the time of flight of a returned light pulse.

SUMMARY

In some embodiments, a lidar system comprises: a light source configured to emit a pulse of light; a scanner configured to: scan a field of view of the light source in a forward-scanning direction across a plurality of pixels located downrange from the lidar system, wherein the plurality of pixels comprises a first pixel and a second pixel, wherein the second pixel is located adjacent to the first pixel along the forward-scanning direction; direct the pulse of light toward the second pixel; and scan a field of view of a first detector of the lidar system, wherein: the first-detector field of view is scanned in the forward-scanning direction across the plurality of pixels; and the first-detector field of view is offset from the light-source field of view in a direction opposite the forward-scanning direction, wherein, when the pulse is emitted: the first-detector field of view at least partially overlaps the first pixel; and the light-source field of view at least partially overlaps the second pixel; and the first detector, wherein the first detector is configured to detect a portion of the pulse of light scattered by a target located at least partially within the second pixel.

In some embodiments, a method comprises: emitting, by a light source of a lidar system, a pulse of light; scanning a field of view of the light source in a forward-scanning direction across a plurality of pixels located downrange from the lidar system, wherein the plurality of pixels comprises a first pixel and a second pixel, wherein the second pixel is located adjacent to the first pixel along the forward-scanning direction; directing the pulse of light toward the second pixel; scanning a field of view of a first detector of the lidar system, wherein: the first-detector field of view is scanned in the forward-scanning direction across the plurality of pixels; and the first-detector field of view is offset from the light-source field of view in a direction opposite the forward-scanning direction, wherein, when the pulse is emitted: the first-detector field of view at least partially overlaps the first pixel; and the light-source field of view at least partially overlaps the second pixel; and detecting a portion of the pulse of light scattered by a target located at least partially within the second pixel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a lidar system **100** capable of improved scanning speed for high-resolution depth mapping.

FIG. **2** illustrates the spatial relationship between a downrange pixel and the field of view of the first detector **130***a* at a scan time which corresponds to a close range target in pixel #1.

FIG. **3** illustrates the spatial relationship between a downrange pixel and the field of view of the first detector **130***a* at a scan time which corresponds to a midrange target in pixel #1.

FIG. **4** illustrates the spatial relationship between a downrange pixel and the field of view of the first detector **130***a* at a scan time which corresponds to a maximum range target in pixel #1.

FIG. **5** illustrates the spatial relationship between a downrange pixel and the field of view of the first detector **130***a* at a scan time which corresponds to a 2× maximum range target in pixel #1.

FIG. **6** is a diagram which shows which pixels are detected together during various ranging periods.

FIG. **7** is a diagram which shows which pixels are detected in each scanning line over time.

FIG. **8** is a diagram of a detector array **128** which includes detectors **130***a-f* spaced apart in two dimensions for simultaneously scanning multiple rows in the field of regard.

FIG. **9** illustrates the spatial relationship between a downrange pixel and the field of view of a detector, where the detector field of view is larger than the pixel.

FIG. **10** is a diagram of a detector array which includes two detectors.

FIG. **11** illustrates forward and reverse scans based on the detector array in FIG. **10**.

FIG. **12** is a diagram of a detector array which includes three detectors.

FIG. **13** illustrates forward and reverse scans based on the detector array in FIG. **12**.

FIG. **14** illustrates an example method for detecting light scattered by a target.

FIG. **15** illustrates an example method for detecting scattered light from angularly separated pulses of light.

DETAILED DESCRIPTION

Lidar systems can be used to determine the distance to a downrange target. By scanning the lidar system across a field of regard, the system can be used to map the distance to a number of points within the field of regard. Each of these points can be referred to as a pixel. It is often desirable that the depth-mapped points within the field of regard be as closely spaced as possible in order to achieve a high resolution depth map of the field of regard. In addition, it is often desirable that the scan time required to create the depth map be as short as possible. For example, it may be desirable to repeatedly complete depth maps of the field of regard at frame rates fast enough to support a depth map video (e.g., **30** frames per second). This disclosure describes a lidar

system **100** which is capable of achieving relatively high resolution depth maps at video frame rates.

FIG. **1** illustrates a lidar system **100** capable of improved scanning speed for high-resolution depth mapping. The lidar system **100** includes a light source **110**. The light source can be, for example, a pulsed laser. The light source **110** emits a pulse of light which propagates toward a collimating lens **112**. After passing through the collimating lens **112**, the pulse of light is transmitted directly through a beam splitter **114** toward a quarter wave plate **116**. The pulse of light then reflects from a scanner **118**. The scanner **118** can be, for example, a scanning mirror **118** that rotates around at least one axis in order to direct light pulses across the field of regard. As an example, the scanner **118** can include a galvanometer scanner, a resonant scanner, a voice coil motor, a DC motor, a stepper motor, or a microelectromechanical systems (MEMS) device. In some embodiments, instead of a beam splitter **114** and quarter wave plate **116**, the lidar system **100** may include a mirror configured so that a pulse of light emitted by the light source **110** passes through the mirror. As an example, the mirror may include a hole, slot, or other aperture that the pulse of light passes through as it travels to the scanning mirror **118**. Light that is scattered by the target **122** may propagate back toward the lidar system, and the mirror may reflect this return light toward mirror **124** which then directs the light toward detector lens **126**. Other physical layouts and combinations of optical elements can also be used.

After reflecting from the scanner **118**, the pulse of light is incident upon a holographic element, pixelator, diffractive element, or similar device **120**. The holographic element or pixelator **120** splits the pulse of light into two pulses which now travel along separate angularly-separated paths **140**, **141**. The two pulses of light propagate downrange from the lidar system **100** toward a target **122**. In FIG. **1**, the target **122** is illustrated as being located at the maximum range of the lidar system **100**.

In some embodiments, the angular separation θ imparted by the holographic element or pixelator **120** is such that the distance between the two light pulses at the maximum range of the lidar system corresponds to the width of multiple pixels. For example, the holographic element or pixelator can be designed such that the separation between the two light pulses at the maximum range corresponds to an odd number of pixels greater than or equal to three pixels (e.g., 3, 5, 7, 9, etc.). (The significance of this particular spacing is described below.) In FIG. **1**, four pixels are labeled on the target **122**. One of the light pulses is directed to the first pixel, while the other light pulse is directed to the fourth pixel. Thus, the spacing between the light pulses is three pixels in this embodiment.

The light pulses scatter from the target **122** and a portion of each pulse propagates back toward the lidar system along reciprocal paths **140**, **141**. Each return light pulse is reflected by the scanner **118**, which has since rotated slightly from its position when the pulses were transmitted, toward the quarter wave plate **116**. After passing through the quarter wave plate **116**, the return light pulses are reflected by the beam splitter **114** toward a mirror **124**. (Although FIG. **1** illustrates that the light source **110** and the detector array **128** share an aperture via the beam splitter **114**, other embodiments are possible without a shared aperture.) The mirror **124** reflects the return light pulses toward a detector lens **126**, the detector lens **126** focuses the return light pulses on a detector array **128** located at the focal plane of the lens **126**. As discussed further herein, the detector focal plane array **128** includes at least two spatially-separated detectors **130***a*, **130***b*. The separation between the two detectors **130***a*, **130***b* is in the scanning dimension of the lidar system **100**. As shown in FIG. **1**, the return light pulse from pixel #1 is focused on the first detector **130***a*, while the return light pulse from pixel #4 is focused on the second detector **130***b*. Thus, the separation between the two detectors **130***a*, **130***b* corresponds to the spacing between the light pulses at the maximum range of the lidar system **100**. Consequently, the separation between the detectors **130***a*, **130***b* likewise corresponds to the spacing between an odd number of pixels greater than or equal to three. (Once again, the significance of this spacing is discussed below.)

The detectors **130***a*, **130***b* create electrical signals which are indicative of the return light pulses. The electrical signals are fed to a processor **132** which then determines the distance to the target **122** based on, for example, the time of flight of the light pulses. This process is repeated as the scanner **118** traverses the field of regard in order to create a depth map of the scene. The processor **132** can also be used to control the timing of light pulses from the light source **110** and other functions of the lidar system **100**.

FIG. **2** illustrates the spatial relationship between a downrange pixel and the field of view of the first detector **130***a* at a scan time which corresponds to a close range target in pixel #1. The size of the pixel depends on the size of the angular field of view of the light source **110** and the distance to the downrange target **122**. In some embodiments, the light source **110** has an angular field of view on the order of milliradians, though it could be larger or smaller depending upon the application. In some embodiments, the angular field of view of each detector **130***a*, **130***b* is substantially equal to that of the light source **110**, though this is not necessarily required. As illustrated, though, in FIG. **2**, the pixel and the detector field of view have the same size.

The lidar system **100** is designed such that each detector **130***a*, **130***b* is aligned with a downrange pixel that is respectively offset from one of the downrange pixels with which the light source **110** is aligned (the light source **110** is aligned with two downrange pixels simultaneously because of the pixelator **120**). For example, in some embodiments, the detectors **130***a*, **130***b* are aimed at the two pixels directly adjacent (in the direction opposite the scanning direction) to the respective downrange pixels with which the light source is aligned.

With reference to FIG. **2**, the light source **110** emits a pulse of light at a time t_1 when the scanner **118** is positioned so as to direct the first pulse toward pixel #1 (and the second pulse toward pixel #4). The scanner **118** continues to scan (left to right) to the next pixel after the pulse of light is emitted (and subsequently split into two pulses). Because the field of view of the first detector **130***a* is offset from that of the light source in the direction opposite the scanning direction, the field of view of the first detector **130***a* does not align with pixel #1 until a subsequent time after t_1.

In FIG. **2**, a relatively short period of time has passed since the light pulse was emitted. Therefore, the field of view of the detector **130***a* slightly overlaps pixel #1. If a return pulse were received by the detector **130***a* at the time illustrated in FIG. **2**, then the processor **132** would register detection of a close range target **122** owing to the short elapsed time of flight. Although the detector field of view only partially overlaps with pixel #1 in the case of a close range target, the return pulse is still strong enough to be detected because the 1/r^2 signal loss is small owing to the relatively close range of the target.

FIG. **3** illustrates the spatial relationship between a downrange pixel and the field of view of the first detector **130***a* at

a scan time which corresponds to a midrange target in pixel #1. At this scan time, the field of view of the detector **130***a* overlaps pixel #1 by a greater amount than was the case for the short-range target in FIG. **2**. This is due to the greater elapsed scanning time since t_1. Because of the greater overlap between the field of view of the detector **130***a* and pixel #1, the greater 1/r^2 signal loss resulting from a more distant target is at least partially offset. The detector **130***a* is therefore able to detect the return pulse from the midrange target.

FIG. **4** illustrates the spatial relationship between a down-range pixel and the field of view of the first detector **130***a* at a scan time which corresponds to a maximum range target in pixel #1. As illustrated by FIG. **4**, the scanning speed of the scanner **118** can be set such that the field of view of the first detector **130***a* substantially completely overlaps pixel #1 at a scan time which corresponds to the round-trip time for a target **122** located at the maximum range of the lidar system **100**. (In other words, in the case of the illustrated example, the time required for the scanner to move the width of one pixel is about the same as the round trip time for the maximum range of the system **100**; the time to completely traverse one pixel from one side to the other is about 2× the round trip time for the maximum range.) It is advantageous for the field of view of the detector to substantially completely overlap pixel #1 for a maximum range target in order to at least partially offset the greater 1/r^2 signal loss which results from the round-trip propagation distance associated with the maximum range of the lidar system.

A comparison of FIG. **4** with FIG. **2** reveals that, at a scan time corresponding to a maximum range target for pixel #1, the detector field of view is in the same position relative to pixel #2 as it was relative to pixel #1 when the scan of pixel #1 began. This might suggest that the detector can begin scanning pixel #2 at this time. The problem with doing so, however, is that a target located in pixel #1 just beyond the maximum range of the lidar system **100** could be confused for a short-range target located in pixel #2. One way to avoid this ambiguity would be to pause or reduce the scanning speed of the scanner **118**. Another way to avoid the ambiguity would be to decrease the scanning resolution. However, neither of these solutions is particularly desirable. The lidar system **100** illustrated in FIG. **1** instead uses a better solution.

As shown in FIG. **1**, the detector array **128** includes two spatially-separated detectors **130***a*, **130***b*. And, as already discussed, the two detectors **130***a*, **130***b* are offset from one another in the scanning direction by a distance which corresponds to an odd number of pixels greater than or equal to three. Specifically, in FIG. **1**, the detectors are offset from one another by a distance corresponding to three pixels. Thus, when the first detector **130***a* is aligned with pixel #1, the second detector **130***b* is aligned with pixel #4. Furthermore, because of the presence of the holographic element or pixelator **120**, when a pulse of light is emitted toward pixel #1, another pulse of light is also emitted toward pixel #4. This means that pixel #1 and pixel #4 can be simultaneously detected by the two detectors **130***a*, **130***b*.

As just discussed above with respect to FIG. **4**, there are disadvantages associated with beginning to scan pixel #2 when the scanner **118** is in position for the first detector **130***a* to do so. For the same reasons, there are also disadvantages associated with beginning to scan pixel #5 when the scanner is in position for the second detector **130***b* to do so. This is because of the risk of misidentifying distant targets—beyond the maximum range of the system—located in pixels #1 and #4 as short-range targets located in pixels #2 and #5, respectively. This risk can be alleviated by skipping pixel #2 and pixel #5 at this time (i.e., not emitting laser pulses toward these pixels at this time) and instead waiting until the scanner **118** is in position for the first detector **130***a* to scan pixel #3 and the second detector **130***b* to scan pixel #6. This is illustrated in FIG. **5**.

FIG. **5** illustrates the spatial relationship between a down-range pixel and the field of view of the first detector **130***a* at a scan time which corresponds to a 2× maximum range target in pixel #1. At this scanning position, there is a diminished risk of falsely detecting a target in pixel #1 because such a target would be located at twice the maximum range of the system and a return light pulse would incur a relatively large amount of 1/r^2 loss associated with that distance. The signal associated with any such return would possibly not rise above the noise floor of the system. (Nevertheless, if the risk of misidentifying the range of a target in a pixel is deemed too great even at a distance of 2× the maximum range of the system, then the first and second detectors **130***a*, **130***b* can instead be separated by a distance which corresponds to 5, 7, 9, etc. pixels.) At the scanning position illustrated in FIG. **5**, the first detector **130***a* is in position to begin scanning pixel #3. Though not illustrated, the second detector **130***b* would similarly be in position to begin scanning pixel #6. Thus, the processor **132** can cause the light source **110** to emit a pulse of light at the scanner position. As already discussed herein, the pulse of light is divided by the holographic element or pixelator **120** so as to cause pulses to be sent toward both pixel #3 and pixel #6 at the same time. These pixels are then ranged by the detectors **130***a*, **130***b* (in the same manner illustrated in FIGS. **2-4**) as the scanner **118** continues its progress across the field of regard.

FIG. **6** is a diagram which shows which pixels are detected together during various ranging periods. Pixels which are detected in a particular ranging period are indicated in FIG. **6** with stars, while pixels which are not detected during that ranging period are crossed out or are not shown. As already discussed herein, in some embodiments, the first and second detectors **130***a*, **130***b* are spatially separated such that they are in position to simultaneously range/detect pixels which are spaced apart in the scan direction by three pixels. Thus, during the first ranging period, pixels #1 and #4 are detected. During the second ranging period, pixels #3 and #6 are detected. During the third ranging period, pixels #5 and #8 are detected, and so on. In this way, the first detector **130***a* detects odd pixels, while the second detector **130***b* detects even pixels.

FIG. **7** is a diagram which shows which pixels are detected in each scanning line over time. As shown in the diagram, every pixel in the scanning line is detected with the exception of pixel #2. In many applications, this trade-off will be acceptable in order to achieve higher scanning speeds and increased resolution. However, if it is necessary to scan every pixel in the line, then the scanner **118** can be configured to scan one or more additional pixels at the tail end of the line in order to compensate.

FIG. **8** is a diagram of a detector array **128** which includes detectors **130***a-f* spaced apart in two dimensions for simultaneously scanning multiple rows in the field of regard. Each row of detectors in the detector array **128** can scan a line in the field of regard at the same time. As illustrated, detectors **130***a* and **130***b* can scan line #1 in the manner already discussed herein. Simultaneously, detectors **130***c* and **130***d* can scan line #5 and detectors **130***e* and **130***f* can scan line #9. By spacing the detectors out in the vertical axis, the scanner can simply reverse direction and move the line of

sight down one line to achieve the scan. Otherwise, the scan would be delayed by the time the vertical portion of the scan traverses the number of detector lines before the next scan line(s) are initiated. However, other arrangements and spacings between the detectors in the direction perpendicular to the scanning direction are also possible.

In some embodiments, a lidar system **100** may include a light source **110**, a scanner **118**, and a detector (e.g., detector **130***a*). The scanner **118** may be configured to scan a field of view of the light source **110** in a scanning direction across multiple pixels (e.g., pixels #1-#3 illustrated in FIGS. **1-5** or pixels #1-#8 illustrated in FIGS. **6-7**) located downrange from the lidar system. The pixels may include pixel #1 and pixel #2, where pixel #2 is located adjacent to pixel #1 along the scanning direction. Pixel #2 being located adjacent to pixel #1 along the scanning direction may indicate that the light-source field of view begins to scan across pixel #1 prior to scanning across pixel #2 (i.e., pixel #1 is scanned before pixel #2). As an example, if the scanning direction is from left to right (e.g., as indicated in FIGS. **2-5**), then pixel #2 is located to the right of pixel #1. The scanning direction indicated in FIGS. **2-5** (e.g., from left to right) may be referred to as a forward-scanning direction, and a direction that is substantially opposite the forward-scanning direction (e.g., from right to left) may be referred to as a reverse-scanning direction.

In some embodiments, a pixel may represent or may correspond to a field of view of the light source **110**. As the light-source beam propagates away from the light source **110**, the diameter of the beam (as well as the size of a corresponding pixel) may increase according to the beam divergence. As an example, if the light source **110** has a divergence of 1 milliradian (mrad), then at a distance of 100 m from the light source **110**, the light-source beam may have a size or diameter of approximately 10 cm, and a corresponding pixel may also have a corresponding size or diameter of approximately 10 cm. At a distance of 200 m from the light source **110**, the light-source beam and the corresponding pixel may each have a diameter of approximately 20 cm.

In some embodiments, the light source **110** may emit a pulse of light at a time t_1, and the scanner **118** may direct the pulse of light toward pixel #2 (e.g., when the pulse is emitted, the light-source field of view may partially, substantially, or completely overlap pixel #2). The scanner **118** may also be configured to scan a field of view of detector **130***a* across the pixels in the same scanning direction as the light-source field of view is scanned. In some embodiments, the detector **130***a* field of view may be offset from the light-source field of view in a direction opposite the scanning direction (e.g., the field of view of detector **130***a* lags behind the light-source field of view). The offset between the detector and light-source fields of view may be such that, at time t_1 when the pulse is emitted, the field of view of detector **130***a* at least partially overlaps pixel #1, and the light-source field of view at least partially overlaps pixel #2 (e.g., the field of view of detector **130***a* lags behind the light-source field of view by approximately one pixel). As an example, at time t_1, the field of view of detector **130***a* may overlap substantially all (e.g., greater than or equal to 80%) of pixel #1 (e.g., as illustrated in FIG. **4**), and the light-source field of view may overlap substantially all (e.g., greater than or equal to 80%) of pixel #2. Additionally, at time t_1, the field of view of detector **130***a* may overlap less than 10% of pixel #2, and the light-source field of view may overlap less than 10% of pixel #1. The detector field of view may be any suitable size relative to the light-source field of view. As an example, the angular size of the detector field of view may be smaller than, substantially the same size as, or larger than the angular size of the light-source field of view.

In some embodiments, detector **130***a* may be configured to detect a portion of the pulse of light which is scattered by a target located at least partially within pixel #2. The portion of the pulse of light may be detected at any suitable time after t_1 when the pulse is emitted (e.g., detector **130***a* may detect the portion of the pulse at a time t_2, where $t_2>t_1$). In some embodiments, lidar system **100** may include a processor **132** which determines a distance from the lidar system **100** to the target based at least in part on a time of flight of the pulse of light, where the time of flight is (t_2-t_1). If lidar system **100** measures a time of flight of Δt (e.g., Δt, which equals t_2-t_1, represents the round-trip time for light to travel from the lidar system **100** to a target and back to the lidar system **100**), then the distance D from the target to the lidar system **100** may be expressed as $D=\cdot\Delta t/2$, where c is the speed of light (approximately 3.0×10^8 m/s). As an example, if a time of flight is measured to be $\Delta t=300$ ns, then the distance from the target **122** to the lidar system **100** is approximately D=45.0 m.

If the distance from the lidar system **100** to the target **122** corresponds to a maximum range of the lidar system **100**, then a round-trip time corresponding to the maximum range of the lidar system is approximately (t_2-t_1), and at time t_2 (when the detector detects the scattered portion of the emitted pulse) the field of view of detector **130***a* overlaps substantially all (e.g., greater than or equal to 80%) of pixel #2. The maximum range of lidar system **100** may be any suitable distance, such as for example, 100 m, 200 m, 500 m, or 1 km. As an example, if the maximum range is 200 m, then the time of flight corresponding to the maximum range is approximately $2\cdot(200\text{ m})/c\cong1.33\ \mu s$. In some embodiments, if the target is a close-range target located within 20% of the maximum range of the lidar system **100**, then at time t_2 (when the detector detects the scattered portion of the emitted pulse) the detector field of view may overlap less than or equal to 20% of pixel #2. In some embodiments, if the target is a midrange target located between 20% and 80% of the maximum range of the lidar system **100**, then at time t_2 the detector field of view may overlap between 20% and 80% of pixel #2. In some embodiments, if the target is located a distance greater than or equal to 80% of the maximum range of the lidar system **100**, then at time t_2 the detector field of view may overlap greater than or equal to 80% of pixel #2.

In some embodiments, the field of view of detector **130***a* and the light-source field of view may have approximately the same scanning speed. As an example, the detector field of view and the light-source field of view may each scan a width of one pixel in a time that is approximately equal to the round-trip time corresponding to the maximum range of the lidar system **100**. In some embodiments, the detector field of view being offset from the light-source field of view in the direction opposite the scanning direction may result in the detector field of view being aligned with pixel #2 at a time t_3, where t_3 is greater than t_1, t_3 is greater than or equal to t_2, and (t_3-t_1) corresponds to the round-trip time for the maximum range of the lidar system **100**. As an example, the light source may emit a pulse of light toward pixel #2 at time t_1, and a corresponding return signal from pixel #2 may be received at a subsequent time t_2. The detector field of view may be aligned with pixel #2 at time t_3, where time t_3 occurs after time t_1 (e.g., time $t_3>t_1$), and the time (t_3-t_1) corresponds to the round-trip time for the maximum range of the lidar system **100**. If the return signal from pixel #2 includes

scattered light from a target located at the maximum range, then t_3 may be approximately equal to t_2 (e.g., the light is received at approximately the same time as the detector field of view is aligned with pixel #2). Otherwise, if the return signal from pixel #2 originates from a target located closer than the maximum range, then t_3 is greater than t_2 (e.g., the light is received at time t_2 before the detector field of view is substantially aligned with pixel #2 at time t_3).

In some embodiments, after emitting a pulse of light at a time t_1, the light source **110** may be configured to emit another pulse of light at a time t_4. The subsequent pulse of light may be emitted at a time when the detector field of view is aligned with pixel #2 or at a subsequent time. The detector field of view may be aligned with pixel #2 at a time t_3, where (t_3-t_1) corresponds to the round-trip time for the maximum range of the lidar system **100**, and the light source **110** may emit the subsequent pulse of light at time t_4, where t_4 is greater than or equal to t_3. Additionally, the pixels may include pixel #3 located adjacent to pixel #2 along the scanning direction, and at time t_4 when the pulse is emitted, the field of view of the light source **110** may be aligned to direct the pulse toward pixel #3.

FIG. **9** illustrates the spatial relationship between a down-range pixel and the field of view of a detector, where the detector field of view (FOV) is larger than the pixel. In some embodiments, the angular size of a detector field of view may be greater than the angular size of the light-source field of view. As an example, a detector field of view may be approximately 1.5×, 2×, 3×, 4×, 5×, or 10× larger than the size of a pixel (which corresponds to the field of view of light source **110**). In FIG. **9**, the detector FOV is approximately 2.5 times larger than pixel #1 (e.g., the diameter of the detector FOV is approximately 2.5 times the diameter of pixel #1). As another example, the divergence of the detector FOV may be approximately 1.5×, 2×, 3×, 4×, 5×, or 10× larger than the divergence of the light-source FOV. If the detector FOV has a 3-mrad divergence and the light-source FOV has a 1-mrad divergence, then at any particular distance from the light source **110**, the detector FOV is 3 times larger than the light-source FOV. For example, at a distance of 100 m from the light source **110**, the light-source beam (which corresponds to pixel #1) may have a diameter of approximately 10 cm, and the detector FOV may have a diameter of approximately 30 cm. At a distance of 200 m, the light-source beam may have a diameter of approximately 20 cm, and the detector FOV may have a diameter of approximately 60 cm.

In some embodiments, a lidar system **100** may perform a series of forward and reverse scans. As an example, a forward scan may include the detector FOV being scanned horizontally from left to right, and a reverse scan may include the detector being scanned from right to left, or vice versa. As another example, a forward scan may include the detector FOV being scanned vertically (e.g., scanning upward or downward), and a reverse scan may include the detector FOV being scanned in the opposite direction. As another example, a forward scan may include the detector FOV begin scanned along any suitable direction (e.g., along a 45-degree angle), and a reverse scan may include the detector FOV being scanned along a substantially opposite direction.

As illustrated in FIG. **9**, the detector FOV may be scanned along a left-to-right direction during a forward scan, and the detector FOV may be scanned along a right-to-left direction during a reverse scan. In some embodiments, the forward and reverse scans may trace paths that are adjacent to or displaced with respect to one another. As an example, a reverse scan may follow a line in the field of regard that is displaced above, below, to the left of, or to the right of a previous forward scan. As another example, a reverse scan may scan a row in the field of regard that is displaced below a previous forward scan, and the next forward scan may be displaced below the reverse scan. The forward and reverse scans may continue in an alternating manner with each scan being displaced with respect to the previous scan until a complete field of regard has been covered. Scans may be displaced with respect to one another by any suitable angular amount, such as for example, by approximately 0.05°, 0.1°, 0.2°, 0.5°, 1°, or 2°.

In some embodiments, a lidar system **100** may be configured so that the detector FOV is larger than the light-source FOV, and the detector and light-source FOVs are substantially coincident or overlapped. The light source **110** may emit a pulse of light toward pixel #1 (e.g., when the pulse is emitted, the light-source FOV may partially, substantially, or completely overlap pixel #1). The FOV of a detector may be larger than the light-source FOV, and when the pulse of light is emitted toward pixel #1, the detector FOV may contain and may be approximately centered on pixel #1. As illustrated in FIG. **9**, the detector FOV may not have any substantial offset with respect to the light-source FOV, and as the pulse of light propagates to and from a target, the detector FOV scans to the right during a forward scan and to the left during a reverse scan. The size of the pixel #1 and the detector FOV may be configured so that during a forward or reverse scan, the detector FOV may substantially contain pixel #1 at least until a round-trip time corresponding to the maximum range of the lidar system has elapsed. When the round-trip time corresponding to the maximum range of the lidar system has elapsed, the detector FOV may have moved so that the pixel #1 is located at or near the left or right edge of the detector FOV. For example, during a forward scan, after the round-trip time corresponding to the maximum range has elapsed, the left edge of pixel #1 may be substantially coincident with the left edge of the detector FOV.

FIG. **10** is a diagram of a detector array **128** which includes two detectors **130***g*, **130***h*. In some embodiments, a lidar system **100** may include a detector array **128** with a first detector **130***g* and a second detector **130***h*. As an example, each of the detectors **130***g* and **130***h* may be an avalanche photodiode (APD) or a single-photon avalanche diode (SPAD). As another example, each of the detectors **130***g* and **130***h* may be a PN photodiode (e.g., a photodiode structure formed by a p-type semiconductor and a n-type semiconductor) or a PIN photodiode (e.g., a photodiode structure formed by an undoped intrinsic semiconductor region located between p-type and n-type regions). The detectors **130***g*, **130***h* may each have an active region or an avalanche-multiplication region that includes silicon, germanium, or InGaAs. The active region or avalanche-multiplication region may have any suitable size, such as for example, a diameter or width of approximately 50-500 μm.

FIG. **11** illustrates forward and reverse scans based on the detector array in FIG. **10**. In some embodiments, a lidar system **100** may include a light source **110**, a scanner **118**, and a detector array **128** with two detectors **130***g*, **130***h*. The two detectors **130***g* and **130***h* may be offset from one another along a direction corresponding to the light-source scanning direction, and the field of view of the light source **110** may be located between the FOVs of detectors **130***g* and **130***h*. The scanner **118** may be configured to scan the light-source FOV (as well as the FOVs of detectors **130***g* and **130***h*) in a forward-scanning direction and in a reverse-scanning direc-

tion across multiple pixels located downrange from the lidar system. As an example, the scanner **118** may scan the light-source FOV (and the detector FOVs) along the forward-scanning direction, and then the scanner **118** may reverse direction and make a subsequent scan along the reverse-scanning direction. As discussed herein, forward and reverse scans may trace paths that are adjacent to or displaced with respect to one another. The forward and reverse scans may be performed alternately with each reverse scan displaced with respect to the previous forward scan, and each forward scan displaced with respect to the previous reverse scan. As an example, a forward scan may follow a substantially horizontal path, and for the subsequent reverse scan, the scanner **118** may deflect the light-source FOV (as well as the FOVs of detectors **130***g* and **130***h*) vertically by some angle (e.g., 0.5°).

In FIG. **11**, the forward scan traces across pixel #1 horizontally from left to right, and the reverse scan traces from right to left across pixel #2, which is located below pixel #1. In some embodiments, the field of view of detector **130***g* may be offset from the light-source field of view in a direction opposite the forward-scanning direction (which corresponds to the reverse-scanning direction), and the field of view of detector **130***h* may be offset from the light-source field of view in the forward-scanning direction. In the forward scan illustrated in FIG. **11**, the FOV of detector **130***h* leads the light-source FOV (corresponding to pixel #1), and the FOV of detector **130***g* lags behind the light-source FOV. In the reverse scan, the relative orientation of the detectors is interchanged so that the FOV of detector **130***g* leads the light-source FOV (corresponding to pixel #2), and the FOV of detector **130***h* lags behind the light-source FOV. In some embodiments, during a forward scan, the lidar system **100** may use a signal from detector **130***g* to determine a distance to a target, and during a reverse scan, the lidar system **100** may use a signal from detector **130***h* to determine a distance to a target. In some embodiments, a signal generated by detector **130***h* may be disregarded during a forward scan, and a signal generated by detector **130***g* may be disregarded during a reverse scan.

In some embodiments, during a forward scan, the light source **110** may emit a pulse of light, and the scanner **118** may direct the pulse of light toward pixel #1. When the pulse is emitted, the FOVs of detector **130***g* and **130***h* may each overlap less than or equal to 20% of pixel #1. The scanner **118** may scan the FOVs of detector **130***g* and **130***h* along the forward-scanning direction (e.g., left to right in FIG. **11**), and detector **130***g* may detect a portion of the pulse of light which is scattered by a target located downrange from the lidar system **100**. As time progresses, the overlap of detector **130***h* FOV with pixel #1 may decrease until there is no overlap, and the overlap of detector **130***g* FOV with pixel #1 may increase until it reaches a maximum overlap (e.g., greater than or equal to 80% overlap). The maximum overlap between detector **130***g* FOV and pixel #1 may occur at a time that corresponds to the maximum range of the lidar system, and after that, the overlap between detector **130***g* FOV and pixel #1 may decrease as the forward scan continues.

In some embodiments, during a reverse scan, the light source **110** may emit another pulse of light, and the scanner **118** may direct the pulse of light toward pixel #2. When the pulse is emitted, the FOVs of detector **130***g* and **130***h* may each overlap less than or equal to 20% of pixel #2. The scanner **118** may scan the FOVs of detector **130***g* and **130***h* along the reverse-scanning direction (e.g., right to left in FIG. **11**), and detector **130***h* may detect a portion of the pulse of light which is scattered by a target located downrange from the lidar system **100**. As time progresses, the overlap of detector **130***g* FOV with pixel #2 may decrease until there is no overlap, and the overlap of detector **130***h* FOV with pixel #2 may increase until it reaches a maximum overlap (e.g., greater than or equal to 80% overlap). The maximum overlap between detector **130***h* FOV and pixel #2 may occur at a time that corresponds to the maximum range of the lidar system, and after that, the overlap between detector **130***h* FOV and pixel #2 may decrease as the reverse scan continues.

In some embodiments, a detector array **128** may include two detectors (e.g., a first detector and a second detector), where the first detector is used to detect scattered light during a forward scan, and the second detector is used to detect scattered light during a reverse scan. The lidar system **100** may include an optical element configured to direct scattered light to the first detector during the forward scan and to direct scattered light to the second detector during the reverse scan. As an example, the scanner **118** may be used to apply a first amount of fixed deflection or angular offset during a forward scan so that scattered light from an emitted pulse is directed to the first detector. Similarly, the scanner **118** may apply a second amount of deflection or angular offset during a reverse scan so that scattered light is directed to the second detector. As another example, the lidar system **100** may include an additional deflection mirror or a deflecting element (e.g., a wedged optic) that has two deflection states for directing scattered light to the first or second detector during a forward or reverse scan, respectively. In some embodiments, a lidar system may include one detector configured to detect scattered light during both forward and reverse scans. The lidar system **100** may include an optical element that provides two states for the orientation of the detector FOV. During a forward scan, the detector FOV may be oriented so that it lags the light source FOV and detects scattered light from emitted pulses, and during a reverse scan, the detector FOV may be oriented so that it also lags the light source FOV.

In some embodiments, a lidar system **100** may include a light source **110**, a splitter **120**, a scanner **118**, and a detector array **128**. The light source **110** may emit pulses of light, and the splitter **120** may split each emitted pulse of light into two or more pulses of angularly separated light. The pulses may be separated by any suitable angle Θ, such as for example, 1 mrad, 2 mrad, 5 mrad, 10 mrad, 20 mrad, or 50 mrad. The scanner **118** may scan pulses of light, which are emitted by the light source **110** and split by the splitter **120**, along a scanning direction across pixels located downrange from the lidar system **100**. The detector array **128** may include two or more detectors. As an example, the splitter **120** may split an emitted pulse into two pulses of angularly separated light (e.g., a first pulse and a second pulse), and the detector array **128** may include a first detector **130***a* and a second detector **130***b*. The first and second detectors may be separated by a detector-separation distance along a direction corresponding to the scanning direction of the light pulses. The first detector may be configured to detect scattered light from the first pulse of light, and the second detector may be configured to detect scattered light from the second pulse of light. In some embodiments, the lidar system **100** may also include a processor configured to determine one or more distances to one or more targets based at least in part on a time of flight of the first pulse of light or a time of flight of the second pulse of light.

In some embodiments, the splitter **120** may include a holographic optical element, a diffractive optical element, a

polarizing beam splitter, a non-polarizing beam splitter, or a beam splitter with a metallic or dielectric coating. As an example, the splitter **120** may include a beam splitter that is manufactured using a holographic process, or the splitter **120** may include a diffractive beam splitter. As another example, the splitter **120** may include a holographic element or a diffractive element that divides an input beam into two or more output beams. In some embodiments, the splitter **120** may be positioned after the scanner **118** so that the splitter **120** receives the emitted pulses of light from the scanner **118**. As illustrated in FIG. **1**, the scanner **118** receives pulses of light emitted by the light source **110**, and the splitter **120** is positioned after the scanner **118** to receive the pulses from the scanner **118**. In some embodiments, the scanner **118** may be positioned after the splitter **120** so that the splitter **120** receives pulses of light emitted by the light source **110**, and the scanner **118** receives pulses of light after they are split by the splitter **120**.

In some embodiments, the splitter **120** may be configured to split a pulse of light substantially equally into two pulses. As an example, the splitter **120** may receive one pulse of light and split it into a first pulse and a second pulse, where the first and second pulses each have approximately one-half of the energy or peak power of the received pulse of light. In some embodiments, the splitter **120** may be configured to split a pulse of light into three pulses of angularly separated light (e.g., a first pulse, a second pulse, and a third pulse). Additionally, the detector array may include three detectors (e.g., a first detector, a second detector, and a third detector), where each detector is configured to receive and detect light from one of the respective pulses of light (e.g., the first detector detects light from the first pulse). In some embodiments, the angularly separated pulses of light from the splitter **120** may be split along a direction corresponding to the scanning direction. As an example, if the scanning direction is substantially horizontal, the angularly separated pulses of light may also be split along the same horizontal direction.

In some embodiments, the light source **110** may emit a pulse of light at a time t_1, and the splitter **120** may split the pulse into two pulses (e.g., a first pulse and a second pulse). The scanner **118** may scan a first light-source field of view associated with the first pulse and a second light-source field of view associated with the second pulse along the scanning direction and across the pixels located downrange from the lidar system **100**. The pixels may include pixel #1, pixel #2, pixel #3, pixel #4, and pixel #5 positioned in order along the scanning direction (e.g., the first or second light-source field of view may scan across the pixels and encounter the pixels in the following order: pixel #1, pixel #2, pixel #3, pixel #4, and pixel #5). In some embodiments, the scanner **118** may direct the first pulse of light toward pixel #2 and the second pulse of light toward pixel #5. Additionally, the scanner **118** may scan a field of view of the first detector and a field of view of the second detector along the scanning direction across the pixels. The first-detector field of view may be offset from the first light-source field of view in a direction opposite the scanning direction, where, at time t_1, the first-detector field of view at least partially overlaps the first pixel, and the first light-source field of view at least partially overlaps the second pixel. Similarly, the second detector field of view may be offset from the second light-source field of view in a direction opposite the scanning direction, where, at time t_1, the second detector field of view at least partially overlaps the fourth pixel, and the second light-source field of view at least partially overlaps the fifth pixel.

In some embodiments, the separation distance between the first and second pulses of light at the maximum range of the lidar system **100** may correspond to the separation distance between detectors **130***a* and **130***b*. As an example, when the first and second pulses of light are incident on a target located at the maximum range of the lidar system **100**, the first and second pulses of light may be separated by a distance that corresponds to the detector-separation distance. When the first and second pulses of light are emitted, their fields of view may overlap pixels #2 and #5, respectively. When the first and second pulses of light return to the lidar system **100** after scattering from the target, the first-detector field of view may overlap pixel #2, and the second detector field of view may overlap pixel #5. In some embodiments, the separation distance between the first and second pulses of light at the maximum range of the lidar system **100** may correspond to an odd number of pixels greater than or equal to three pixels. As an example, at the maximum range, the first and second pulses of light may be separated by a distance corresponding to three pixels so that when the first pulse is directed at pixel #2, the second pulse is directed at pixel #5. In some embodiments, the detector-separation distance may correspond to an odd number of pixels greater than or equal to three pixels. As an example, the detector-separation distance may correspond to three pixels so that when the first detector receives light from pixel #2, the second detector receives light from pixel #5.

FIG. **12** is a diagram of a detector array **128** which includes three detectors **130***i*, **130***j*, and **130***k*. Each of the detectors **130***i*, **130***j*, and **130***k* may be an APD or a SPAD. In some embodiments, a lidar system **100** may include a light source **110**, a scanner **118**, a splitter **120**, and a detector array **128** with three detectors **130***i*, **130***j*, and **130***k*. The three detectors **130***i*, **130***j*, **130***k* may be separated from one another by a detector-separation distance along a direction corresponding to the light-source scanning direction.

FIG. **13** illustrates forward and reverse scans based on the detector array in FIG. **12**. During a forward scan, the splitter **120** may split an emitted pulse into two pulses of angularly separated light (e.g., a first pulse and a second pulse which are directed to pixel #1 and pixel #2, respectively). When the pulse is emitted, the field of view of the first pulse (corresponding to pixel #1) may be located between the FOVs of detectors **130***i* and **130***j*, and the field of view of the second pulse (corresponding to pixel #2) may be located between the FOVs of detectors **130***j* and **130***k*. The detector **130***i* FOV may lag the FOV of the first pulse, and detector **130***i* may be configured to detect scattered light from the first pulse. Similarly, the detector **130***j* FOV may lag the FOV of the second pulse, and detector **130***j* may be configured to detect scattered light from the second pulse. Additionally, during a forward scan, the signal from detector **130***k* may be ignored. In some embodiments, there may be additional pixels (not illustrated in FIG. **13**) located between pixels #1 and #2 (and additional pixels located between pixels #3 and #4).

In some embodiments, the scanner **118** may be configured to scan additional pulses of light, which are emitted by the light source **110** and split by the splitter **120**, along a reverse-scanning direction corresponding to the direction opposite the forward-scanning direction. The light source **110** may emit an additional pulse of light while the scanner **118** is scanning in the reverse-scanning direction. As discussed herein, scans of the reverse-scanning direction may be displaced with respect to the forward-scanning direction. In FIG. **13**, the forward scan traces across pixels #1 and #2, and the reverse scan traces across pixels #3 and #4, which are located below pixels #1 and #2. The splitter **120** may

split the emitted pulse into a third pulse of light and a fourth pulse of light, which are angularly separated. The third pulse may be directed to pixel #3, and the fourth pulse may be directed to pixel #4. When the pulse is emitted, the field of view of the third pulse (corresponding to pixel #3) may be located between the FOVs of detectors **130***j* and **130***k*, and the field of view of the second pulse (corresponding to pixel #4) may be located between the FOVs of detectors **130***i* and **130***j*. During a reverse scan, the detector **130***k* FOV may lag the FOV of the third pulse, and detector **130***k* may be configured to detect scattered light from the third pulse. Similarly, the detector **130***j* FOV may lag the FOV of the fourth pulse, and detector **130***j* may be configured to detect scattered light from the fourth pulse. Additionally, during a reverse scan, the signal from detector **130***i* may be ignored.

A lidar system **100** as described or illustrated herein may also include various elements described or illustrated in U.S. Provisional Patent Application No. 62/243,633, filed 19 Oct. 2015 and entitled "Lidar System with Improved Signal-to-Noise Ratio in the Presence of Solar Background Noise" or U.S. Provisional Patent Application No. 62/261,214, filed 30 Nov. 2015 and entitled "Lidar System with a Distributed Laser and a Plurality of Sensor Heads," each of which is incorporated herein by reference.

FIG. **14** illustrates an example method **400** for detecting light scattered by a target. The method may begin at step **410**, where a light source **110** of a lidar system **100** emits a pulse of light at a time t_1. At step **420**, a field of view of the light source **110** may be scanned in a forward-scanning direction across multiple pixels located downrange from the lidar system **100**. The pixels may include a first pixel and a second pixel, where the second pixel is located adjacent to the first pixel along the forward-scanning direction. At step **430**, the pulse of light may be directed toward the second pixel. At step **440**, a field of view of a first detector of the lidar system **100** may be scanned. The first-detector field of view may be scanned in the forward-scanning direction across the pixels. Additionally, the first-detector field of view may be offset from the light-source field of view in a direction opposite the forward-scanning direction, where, at time t_1, the first-detector field of view at least partially overlaps the first pixel, and the light-source field of view at least partially overlaps the second pixel. At step **450**, a portion of the pulse of light scattered by a target located at least partially within the second pixel may be detected, at which point the method may end. The portion of the pulse of light may be detected at a time t_2, where t_2 is greater than t_1.

FIG. **15** illustrates an example method **500** for detecting scattered light from angularly separated pulses of light. The method may begin at step **510**, where a light source **110** of a lidar system **100** emits a pulse of light. At step **520**, the emitted pulse of light may be split into two or more pulses of angularly separated light. The two or more pulses may be split by a splitter **120** and may include a first pulse of light and a second pulse of light. At step **530**, pulses of light (which are emitted by the light source **110** and split by the splitter **120**) may be scanned along a scanning direction across pixels located downrange from the lidar system **100**. At step **540**, scattered light from the first pulse of light may be detected. At step **550**, scattered light from the second pulse of light may be detected, at which point the method may end. The scattered light from the first and second pulses of light may be detected by a first detector and a second detector, respectively, where the first and second detectors are part of a detector array. The first and second detectors may be separated by a detector-separation distance along a direction corresponding to the scanning direction of the light pulses.

Embodiments have been described in connection with the accompanying drawings. However, it should be understood that the figures are not drawn to scale. Distances, angles, etc. are merely illustrative and do not necessarily bear an exact relationship to actual dimensions and layout of the devices illustrated. In addition, the foregoing embodiments have been described at a level of detail to allow one of ordinary skill in the art to make and use the devices, systems, etc. described herein. A wide variety of variation is possible. Components, elements, and/or steps may be altered, added, removed, or rearranged. While certain embodiments have been explicitly described, other embodiments will become apparent to those of ordinary skill in the art based on this disclosure.

The systems and methods described herein can advantageously be implemented, at least in part, using computer software, hardware, firmware, or any combination of software, hardware, and firmware. Software modules can comprise computer executable code for performing the functions described herein. In some embodiments, computer-executable code is executed by one or more general purpose computers. However, a skilled artisan will appreciate, in light of this disclosure, that any module that can be implemented using software to be executed on a general purpose computer can also be implemented using a different combination of hardware, software, or firmware. For example, such a module can be implemented completely in hardware using a combination of integrated circuits. Alternatively or additionally, such a module can be implemented completely or partially using specialized computers designed to perform the particular functions described herein rather than by general purpose computers. In addition, where methods are described that are, or could be, at least in part carried out by computer software, it should be understood that such methods can be provided on computer-readable media (e.g., optical disks such as CDs or DVDs, hard disk drives, flash memories, diskettes, or the like) that, when read by a computer or other processing device, cause it to carry out the method.

While certain embodiments have been explicitly described, other embodiments will become apparent to those of ordinary skill in the art based on this disclosure. Therefore, the scope of the invention is intended to be defined by reference to the claims and not simply with regard to the explicitly described embodiments.

What is claimed is:

1. A lidar system comprising:

a light source configured to emit a pulse of light;

a scanner configured to:

scan a field of view of the light source in a forward-scanning direction across a plurality of pixels located downrange from the lidar system, wherein the plurality of pixels comprises a first pixel and a second pixel, wherein the second pixel is located adjacent to the first pixel along the forward-scanning direction;

direct the pulse of light toward the second pixel; and

scan a field of view of a first detector of the lidar system, wherein:

the first-detector field of view is scanned in the forward-scanning direction across the plurality of pixels; and

the first-detector field of view is offset from the light-source field of view in a direction opposite the forward-scanning direction,

wherein, when the pulse is emitted:

the first-detector field of view at least partially overlaps the first pixel; and

the light-source field of view at least partially overlaps the second pixel; and

the first detector, wherein the first detector is configured to detect a portion of the pulse of light scattered by a target located at least partially within the second pixel.

2. The lidar system of claim **1**, further comprising a processor configured to determine a distance from the lidar system to the target based at least in part on a time of flight of the pulse of light.

3. The lidar system of claim **1**, wherein if the distance from the lidar system to the target corresponds to a maximum range of the lidar system, then, when the first detector detects the portion of the pulse of light, the first-detector field of view overlaps substantially all of the second pixel.

4. The lidar system of claim **1**, wherein if the target is a close-range target located within 20% of a maximum range of the lidar system, then, when the first detector detects the portion of the pulse of light, the first-detector field of view overlaps less than or equal to 20% of the second pixel.

5. The lidar system of claim **1**, wherein if the target is a midrange target located between 20% and 80% of a maximum range of the lidar system, then, when the first detector detects the portion of the pulse of light, the first-detector field of view overlaps between 20% and 80% of the second pixel.

6. The lidar system of claim **1**, wherein if the target is located a distance greater than or equal to 80% of a maximum range of the lidar system, then, when the first detector detects the portion of the pulse of light, the first-detector field of view overlaps greater than or equal to 80% of the second pixel.

7. The lidar system of claim **1**, wherein an angular size of the first-detector field of view is substantially equal to an angular size of the light-source field of view.

8. The lidar system of claim **1**, wherein the second pixel being located adjacent to the first pixel along the forward-scanning direction corresponds to the light-source field of view beginning to scan across the first pixel prior to scanning across the second pixel.

9. The lidar system of claim **1**, wherein a time for the first detector field of view to scan a width of one pixel is approximately equal to a round-trip time for a maximum range of the lidar system.

10. The lidar system of claim **1**, wherein a time for the light-source field of view to scan a width of one pixel is approximately equal to a round-trip time for a maximum range of the lidar system.

11. The lidar system of claim **1**, wherein the first-detector field of view being offset from the light-source field of view in the direction opposite the forward-scanning direction is such that the first-detector field of view is aligned with the second pixel at a time after the pulse of light is emitted that corresponds to a round-trip time for a maximum range of the lidar system.

12. The lidar system of claim **1**, wherein:

the first-detector field of view is aligned with the second pixel at a time after the pulse of light is emitted that corresponds to a round-trip time for a maximum range of the lidar system; and

the light source is further configured to emit another pulse of light at a time after the first-detector field of view is aligned with the second pixel.

13. The lidar system of claim **1**, further comprising a second detector, wherein a field of view of the second detector is offset from the light-source field of view in the forward-scanning direction.

14. The lidar system of claim **13**, wherein, when the pulse is emitted, the second-detector field of view overlaps less than or equal to 20% of the second pixel.

15. The lidar system of claim **13**, wherein the scanner is further configured to:

scan the light-source field of view in a reverse-scanning direction corresponding to the direction opposite the forward-scanning direction; and

scan the second-detector field of view in the reverse-scanning direction.

16. The lidar system of claim **15**, wherein:

the light source is further configured to emit an additional pulse of light while the scanner is scanning the light-source field of view and the second-detector field of view in the reverse-scanning direction; and

the second detector is configured to detect a portion of the additional pulse of light which is scattered by a target located downrange from the lidar system.

17. The lidar system of claim **15**, wherein:

the forward-scanning direction corresponds approximately to a left-to-right direction; and

the reverse-scanning direction corresponds approximately to a right-to-left direction.

18. A method comprising:

emitting, by a light source of a lidar system, a pulse of light;

scanning a field of view of the light source in a forward-scanning direction across a plurality of pixels located downrange from the lidar system, wherein the plurality of pixels comprises a first pixel and a second pixel, wherein the second pixel is located adjacent to the first pixel along the forward-scanning direction;

directing the pulse of light toward the second pixel;

scanning a field of view of a first detector of the lidar system, wherein:

the first-detector field of view is scanned in the forward-scanning direction across the plurality of pixels; and

the first-detector field of view is offset from the light-source field of view in a direction opposite the forward-scanning direction, wherein, when the pulse is emitted:

the first-detector field of view at least partially overlaps the first pixel; and

the light-source field of view at least partially overlaps the second pixel; and

detecting a portion of the pulse of light scattered by a target located at least partially within the second pixel.

19. The method of claim **18**, further comprising determining a distance from the lidar system to the target based at least in part on a time of flight of the pulse of light.

20. The method of claim **18**, further comprising:

scanning the light-source field of view in a reverse-scanning direction corresponding to the direction opposite the forward-scanning direction;

scanning a field of view of a second detector of the lidar system in the reverse-scanning direction, wherein the second-detector field of view is offset from the light-source field of view in the forward-scanning direction.

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