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(54) Title: THREE-DIMENSIONAL LIDAR SENSOR BASED ON TWO-DIMENSIONAL SCANNING OF ONE-DIMENSION-
AL OPTICAL EMITTER

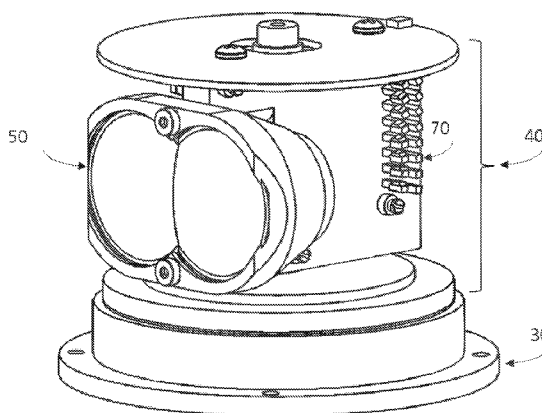


Fig. 3

(57) Abstract: An apparatus and method are used for three-dimensional sensing with a time-of-flight lidar sensor having a single emitter sensing in one dimension, at least one photodetector, and a mechanical means of scanning in two dimensions said emitter and at least one photodetector. The external case of the lidar is preferably static, and only internal components involve mechanical motion. In a preferred embodiment of said lidar when operated in the infrared, said external static case has a window that is visually opaque and essentially transparent to infrared radiation.

THREE-DIMENSIONAL LIDAR SENSOR BASED ON TWO-DIMENSIONAL SCANNING OF ONE-DIMENSIONAL OPTICAL EMITTER

CROSS REFERENCE TO RELATED APPLICATIONS

5 This application claims priority to U.S. patent application no. 14/517,948 filed on October 20, 2014, the contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to the field of environment sensing, and more particularly to cost-effective Time of Flight (ToF) lidar sensor apparatus for
10 three-dimensional mapping and object detection, tracking and/or classification.

BACKGROUND OF THE INVENTION

A lidar sensor is a light detection and ranging sensor. It is an optical remote sensing module that can measure the distance to a target or objects in a landscape, by irradiating the target or landscape with light, using pulses from a laser, and
15 measuring the time it takes photons to travel to said target or landscape and return after reflection to a receiver in the lidar module. Lidar sensors based on mechanical motion achieve a wide field of view. The cost and resolution of mechanical-motion lidar sensors containing multiple discrete individually packaged lasers are not optimal, as having a plurality of individually-packaged lasers is costly and scanning
20 the environment in planes defined by individual collimated lasers does not achieve an acceptable resolution in some applications, especially ones where the lidar mounting platform is static (e.g., on a pole for use in road/intersection/traffic monitoring) or when the lidar mounting platform is generally mobile but has scenarios where it is static (e.g., a vehicle stopped at a traffic light that needs to
25 sense pedestrians across the intersection, a situation where it cannot benefit from the laser beam sweeping obtained when the vehicle is moving/shaking/vibrating).

US 5,455,669 discloses a laser range finding apparatus comprising a mirror mounted for rotation along a vertical axis parallel to the vertical axis of light from a pulsed laser being emitted for deflection into the measurement region, and angularly
30 inclined with respect to the plane of rotation and the vertical axis to cause pulsed light from the collimated laser to be diverted over the planar measurement field and

reflected light from the measurement region to be received from the planar measurement region and diverted along a vertical path to a photoreceiver arrangement.

US 7,746,449 discloses a light detection and ranging system, comprising a collimated laser beam, a mirror unit rotating around a scan axis, the mirror unit including a receiving portion and a transmitting portion offset by an angle about the scan axis relative to a surface plane of the receiving portion, respective centroids of the receiving and transmitting portions being positioned at a common point on the scan axis.

US 7,969,558 discloses a lidar-based 3-D point cloud system comprising a support structure, a plurality of laser emitters supported by the support structure, a plurality of avalanche photodiode detectors supported by the support structure, and a rotary component configured to rotate the plurality of laser emitters and the plurality of avalanche photodiode detectors at a speed of at least 200 RPM (rotations per minute).

US application 2011/0216304 discloses a LiDAR-based sensor system comprising a base, head assembly, a rotary component configured to rotate the head assembly with respect to the base, the rotation of the head assembly defining an axis of rotation; an electrical motherboard carried in the head assembly, the motherboard defining a plane and being positioned substantially parallel to the axis of rotation, a plurality of photon transmitters mounted to a plurality of emitter circuit boards, the plurality of emitter circuit boards being mounted directly to the motherboard, and a plurality of detectors mounted to a plurality of detector circuit boards, the plurality of detector circuit boards being mounted directly to the motherboard.

SUMMARY OF THE INVENTION

An apparatus and method are used for three-dimensional sensing with a time-of-flight lidar sensor having a single emitter and at least one photodetector. Said single emitter can comprise a single laser, a single laser bar, or multiple lasers (preferably in the form of an integrated multi-laser chip, or co-packaged laser chips, or a multi-chip module in a single package), and in all three cases the emitter output is imaged to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing. Said single emitter can also comprise a single laser coupled to

an optical phased array (OPA) that either images a radiation pattern whose envelope is elongated to provide one-dimensional sensing, or sweeps a beam in one dimension to provide one-dimensional sensing. Said single emitter can also comprise a single laser coupled to a diffractive optical element (DOE) or a holographic optical element (HOE), with either optical element imaging a radiation pattern whose envelope is elongated to provide one-dimensional sensing. For all single emitter configurations, a mechanical motion (e.g., spinning or mirror/prism/lens/DOE/HOE/grating scanning) is used to cover the two dimensions not covered by the emitter, resulting in three-dimensional sensing.

When a plurality of photodetectors are used, they preferably comprise an integrated multi-photodetector chip, or co-packaged photodetector chips, or a photodetection multi-chip module.

Photodetector types include single-photon avalanche diode (SPAD) arrays, avalanche photodiodes (APD) and PIN diodes (PIN diodes are positive-intrinsic-negative diodes, as they comprise a lightly-doped intrinsic semiconductor region between a p-type or positive-type semiconductor region and an n-type or negative-type semiconductor region).

As opposed to US 5,455,669 and US 7,746,449, the present invention does not have a static collimated laser in the dimension normal to the plane covered by the mechanical motion, but instead has an emitter than covers said normal dimension through imaging a radiation pattern whose envelope is elongated or through sweeping in said normal dimension.

As opposed to US 7,969,558 and US application 2011/0216304 where the described apparatus comprises a plurality of emitters, the present invention comprises a single emitter. Also, as opposed to APDs, the present invention can use PIN diodes or preferably SPAD arrays. Furthermore, the head assembly is static as opposed to rotating, and only the internal turret is spinning when the mechanical motion consists of spinning, or an optical element (e.g., mirror, prism, lens, DOE, HOE, grating) is scanning when the mechanical motion consists of scanning. The entire external body of the lidar in the present invention is static.

BRIEF DESCRIPTION OF THE DRAWINGS

The following drawings are illustrative of embodiments of the present invention and are not intended to limit the invention as encompassed by the claims forming part of the application.

5 The schematic diagram of Figure 1 provides an external view of the lidar **10** of one embodiment of the lidar of the present invention, depicting its static external case **20**.

10 Figure 2 provides an internal view of one embodiment of the lidar of the present invention angled as to show the emitting side, depicting an internal base **30**, a spinning turret **40**, an optical imaging assembly **50**, and a single emitter **60**.

 Figure 3 provides an internal view of one embodiment of the lidar of the present invention angled as to show the receiving side, depicting an internal base **30**, a spinning turret **40**, an optical imaging assembly **50**, and photodetectors **70**.

DETAILED DESCRIPTION OF THE INVENTION

15 An apparatus and method are used for three-dimensional sensing with a time-of-flight lidar sensor having a single emitter and at least one photodetector.

 Said single emitter can comprise:

- (a) a single laser
- (b) a single laser bar
- 20 (c) multiple lasers (preferably in the form of an integrated multi-laser chip, or co-packaged laser chips, or a multi-chip module in a single package)

 where in cases (a), (b) and (c) the emitter output is imaged to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing

25 (d) a single laser coupled to an optical phased array (OPA) that images a radiation pattern whose envelope is elongated to provide one-dimensional sensing

 (e) a single laser coupled to an optical phased array (OPA) that sweeps a beam in one dimension to provide one-dimensional sensing

 (f) a single laser coupled to a diffractive optical element (DOE)

 (g) a single laser coupled to a holographic optical element (HOE)

30 (h) a single laser coupled to a lens

 where in cases (f), (g) and (h), the optical element images a radiation pattern whose envelope is elongated to provide one-dimensional sensing.

For all single emitter configurations, a mechanical motion is used to cover the two dimensions not covered by the emitter, resulting in three-dimensional sensing. The mechanical motion mechanism options include but are not limited to:

- (a) spinning
- 5 (b) mirror scanning
- (c) prism scanning
- (d) lens scanning
- (e) DOE scanning
- (f) HOE scanning
- 10 (g) grating scanning

When a plurality of photodetectors are used, they preferably comprise but are not limited to the following options:

- (a) an integrated multi-photodetector chip
- (b) co-packaged photodetector chips
- 15 (c) a photodetection multi-chip module

Photodetector types include but are not limited to:

- (a) SPAD arrays
- (b) APDs
- (c) PIN diodes

20 The external case of the lidar in the present invention is preferably static, and only internal components involve mechanical motion. In a preferred embodiment of the present invention when operated in the infrared (IR), the window material of said case is visually opaque and IR transparent.

What is Claimed is:

1. A time-of-flight lidar apparatus comprising:
 - a) a single optical emitter sensing in one dimension;
 - 5 b) at least one photodetector;
 - c) a mechanical means of scanning in two dimensions said emitter and at least one photodetector.
2. The apparatus of claim 1 wherein said single emitter comprises one of a set of
10 elements including but not limited to:
 - a) a single laser imaged to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;
 - b) a single laser bar imaged to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;
 - 15 c) a plurality of lasers integrated on one substrate and imaged to form a continuous radiation pattern whose envelope is elongated to provide one-dimensional sensing;
 - d) a plurality of lasers co-packaged and imaged to form a continuous radiation pattern whose envelope is elongated to provide one-dimensional sensing;
 - 20 e) a single laser coupled to an optical phased array that images a beamformed radiation pattern whose envelope is elongated to provide one-dimensional sensing;
 - f) a single laser coupled to an optical phased array that sweeps a beamformed radiation pattern in one dimension to provide one-dimensional sensing;
 - 25 g) a single laser coupled to a diffractive optical element to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;
 - h) a single laser coupled to a holographic optical element to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;
 - i) a single laser coupled to a lens to form a radiation pattern whose envelope
30 is elongated to provide one-dimensional sensing.
3. The apparatus of claim 1 wherein said at least one photodetector comprises one of a set of elements including but not limited to:
 - a) single-photon avalanche diode arrays;

- b) avalanche photodiodes;
- c) positive-intrinsic-negative diodes.

4. The apparatus of claim 1 comprising a plurality of photodetectors in a form
5 selected from a set comprising but not limited to:

- a) integrated multi-photodetector chip;
- b) co-packaged photodetector chips;
- c) photodetection multi-chip module.

10 5. The apparatus of claim 1 wherein said mechanical means of scanning in two
dimensions said emitter and said at least one photodetector is selected from a set
comprising but not limited to:

- a) spinning
- b) mirror scanning
- 15 c) prism scanning
- d) lens scanning
- e) DOE scanning
- f) HOE scanning
- g) grating scanning

20 6. The apparatus of claim 1 including an external case that is static.

7. The apparatus of claim 6 wherein said external static case has a window that
is visually opaque and essentially transparent to infrared radiation.

25 8. A method for three-dimensional sensing utilizing a time-of-flight lidar
apparatus comprising:

- a) a single optical emitter sensing in one dimension;
- b) at least one photodetector;

30 c) a mechanical means of scanning in two dimensions said emitter and at
least one photodetector.

9. The method of claim 8 wherein said single emitter of said apparatus
comprises one of a set of elements including but not limited to:

a) a single laser imaged to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;

b) a single laser bar imaged to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;

5 c) a plurality of lasers integrated on one substrate and imaged to form a continuous radiation pattern whose envelope is elongated to provide one-dimensional sensing;

d) a plurality of lasers co-packaged and imaged to form a continuous radiation pattern whose envelope is elongated to provide one-dimensional sensing;

10 e) a single laser coupled to an optical phased array that images a beamformed radiation pattern whose envelope is elongated to provide one-dimensional sensing;

f) a single laser coupled to an optical phased array that sweeps a beamformed radiation pattern in one dimension to provide one-dimensional sensing;

15 g) a single laser coupled to a diffractive optical element to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;

h) a single laser coupled to a holographic optical element to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing;

20 i) a single laser coupled to a lens to form a radiation pattern whose envelope is elongated to provide one-dimensional sensing.

10. The method of claim 8 wherein said at least one photodetector of said apparatus comprises one of a set of elements including but not limited to:

a) single-photon avalanche diode arrays;

25 b) avalanche photodiodes;

c) positive-intrinsic-negative diodes.

11. The method of claim 8 wherein said apparatus comprises a plurality of photodetectors in a form selected from a set comprising but not limited to:

30 a) integrated multi-photodetector chip;

b) co-packaged photodetector chips;

c) photodetection multi-chip module.

12. The method of claim 8 wherein said apparatus' said mechanical means of scanning in two dimensions said emitter and said at least one photodetector is selected from a set comprising but not limited to:

- a) spinning
- b) mirror scanning
- c) prism scanning
- d) lens scanning
- e) DOE scanning
- f) HOE scanning
- g) grating scanning

13. The method of claim 8 wherein said apparatus includes an external case that is static.

14. The method of claim 13 wherein said external static case of said apparatus has a window that is visually opaque and essentially transparent to infrared radiation.

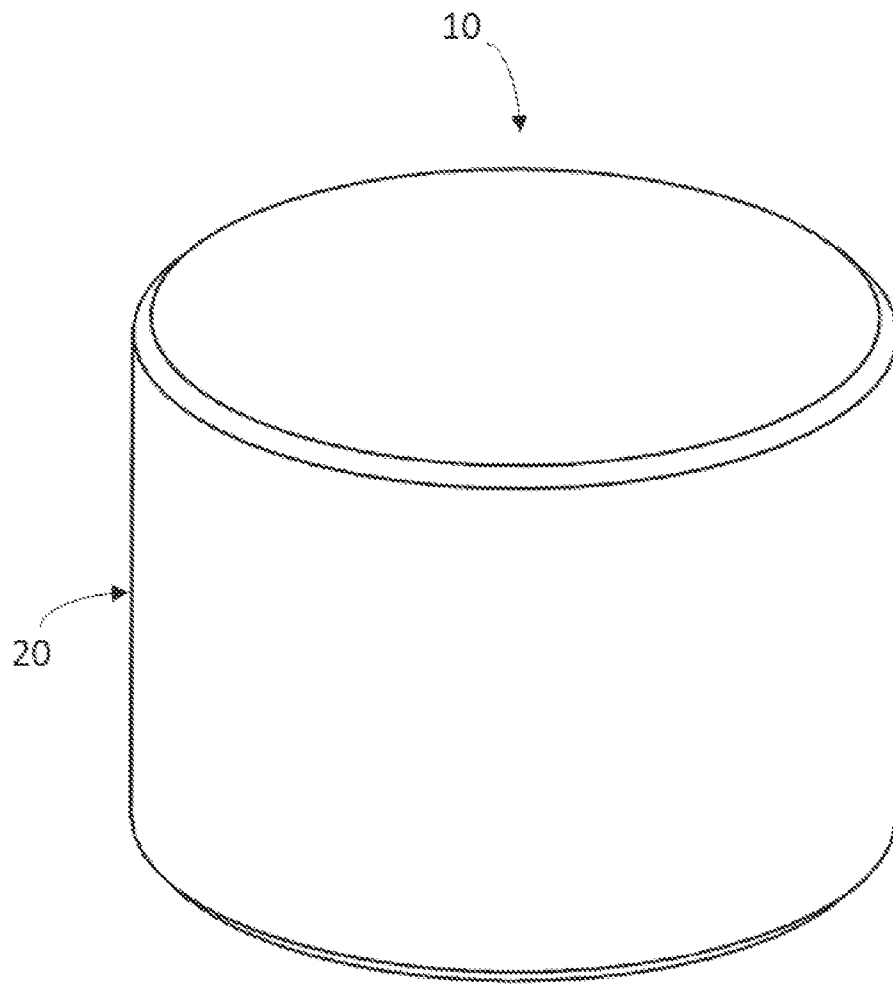


Fig. 1

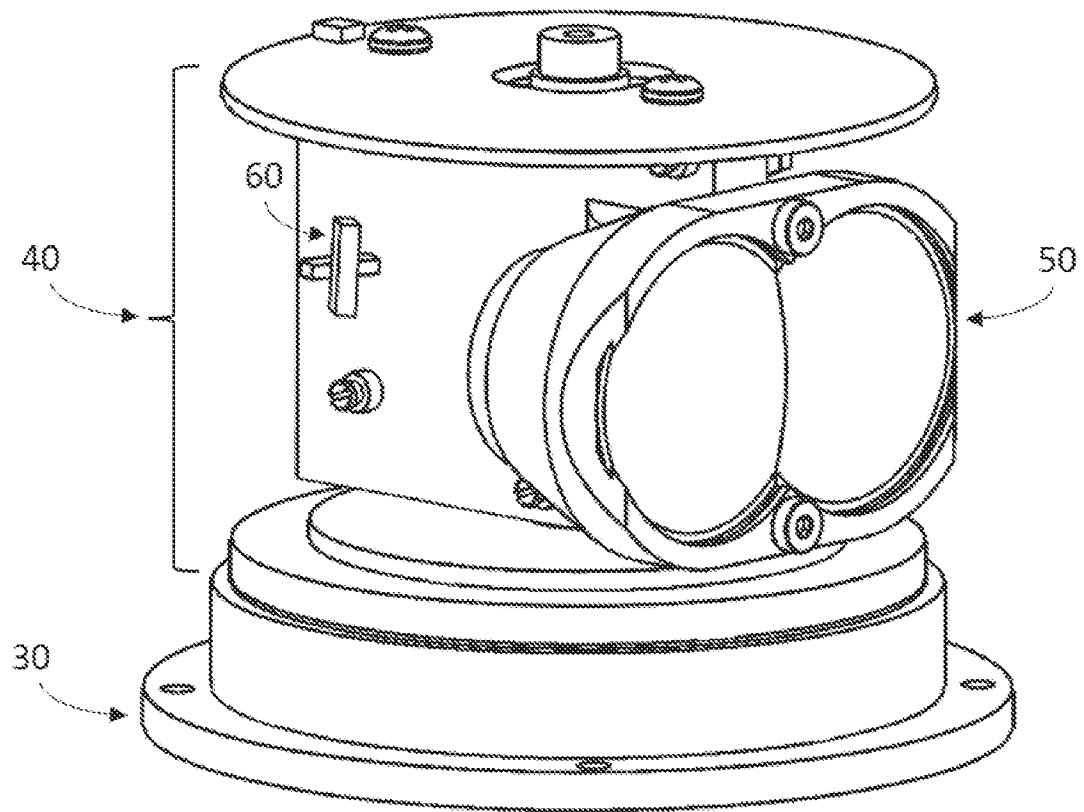


Fig. 2

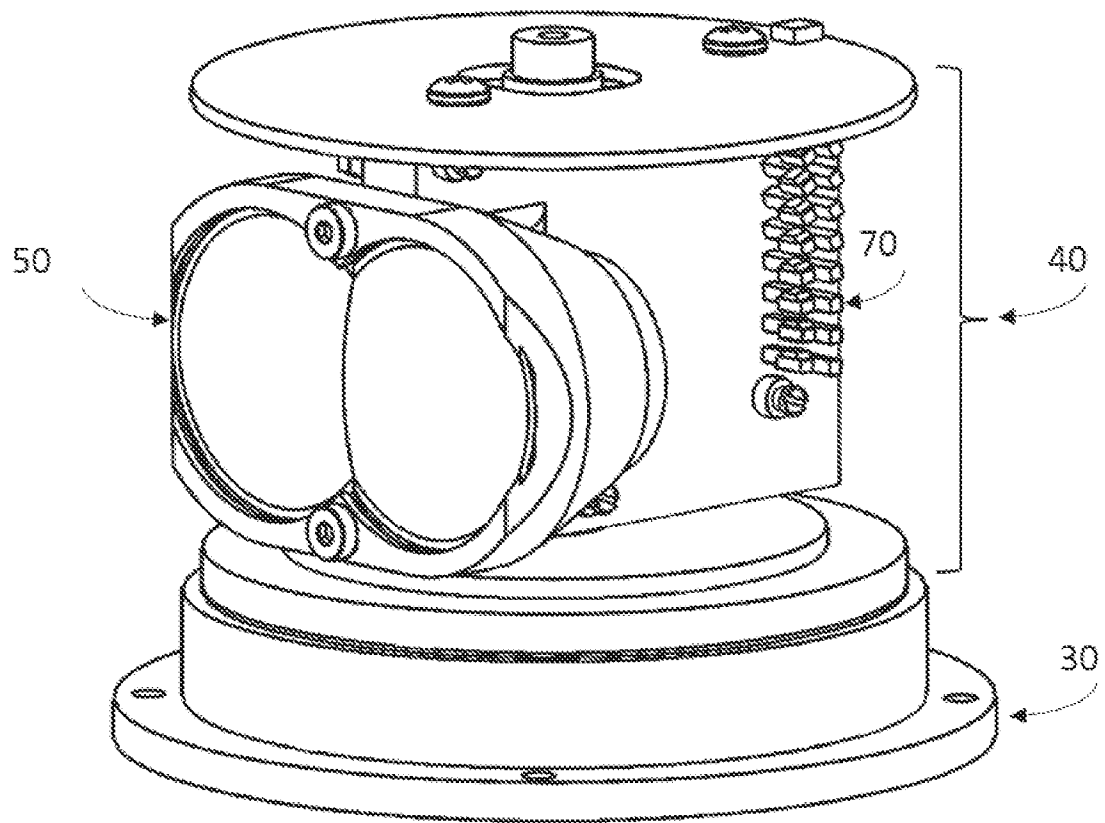


Fig. 3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/56516

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01S 17/00, G01S 17/02, G01S 17/88 (2015.01)

CPC - G01S 17/00, G01S 17/02

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)

IPC(8): G01S 17/00, G01S 17/02, G01S 17/88 (2015.01); CPC: G01S 17/00, G01S 17/003, G01S 17/02, G01S 17/026, G01S 17/06, G01S 17/50, G01S 17/88, G01C 3/08, G01P 3/36

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

IPC(8): G01S 17/00, G01S 17/02, G01S 17/88 (2015.01); CPC: G01S 17/00, G01S 17/003, G01S 17/02, G01S 17/026, G01S 17/06, G01S 17/50, G01S 17/88, G01C 3/08, G01P 3/36; USPC: 356/4.01, 356/5.01, 356/5.09 (keyword limited using search terms below)

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

Patbase; Google Web Search; Google Patent Search

Search Terms Used: Lidar; emitter/transmi*/laser; detect*/sens*/photosensor/photodetect*/receiv*; scan*/rotat*/pivot*/spin*/mirror%

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X — Y	US 8,836,922 B1 (PENNECOT et al.) 16 September 2014 (16.09.2014), figure 2; col. 3, ln 19-33; col. 3, ln 52-col. 4, ln 4; col. 4, ln 16-25; col. 7, ln 28-49; col. 9, ln 45-50	1-5, 8-12 ----- 6, 7, 13, 14
Y	US 2011/0255070 A1 (PHILLIPS et al.) 20 October 2011 (20.10.2011), figure 7; para [0073], para [0076]	6, 7, 13, 14
A	US 2013/0027715 A1 (IMAKI et al.) 31 January 2013 (31.01.2013), entire document	1-14
A	US 2014/0240691 A1 (MHEEN) 28 August 2014 (28.08.2014), entire document	1-14
A	US 2009/0278030 A1 (DELIWALA) 12 November 2009 (12.11.2009), entire document	1-14

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“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

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