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(12) **United States Patent**
Pettersson et al.

(10) **Patent No.: US 9,063,614 B2**
(45) **Date of Patent: Jun. 23, 2015**

(54) **OPTICAL TOUCH SCREENS**

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(73) Assignee: **Neonode Inc.**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/311,366**

(22) Filed: **Jun. 23, 2014**

(65) **Prior Publication Data**

US 2014/0320459 A1 Oct. 30, 2014

Related U.S. Application Data

(63) Continuation of application No. PCT/US2014/040579, filed on Jun. 3, 2014, and a continuation-in-part of application No. 13/052,511, filed on Mar. 21, 2011, which is a continuation-in-part

(Continued)

(51) **Int. Cl.**

G06F 3/042	(2006.01)
G06F 3/041	(2006.01)
G06F 3/0354	(2013.01)

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

CPC ***G06F 3/042*** (2013.01); ***G06F 3/0416*** (2013.01); ***G06F 3/0421*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC G06F 3/0421; G06F 3/0423
USPC 345/175; 178/18.09, 18.11
See application file for complete search history.

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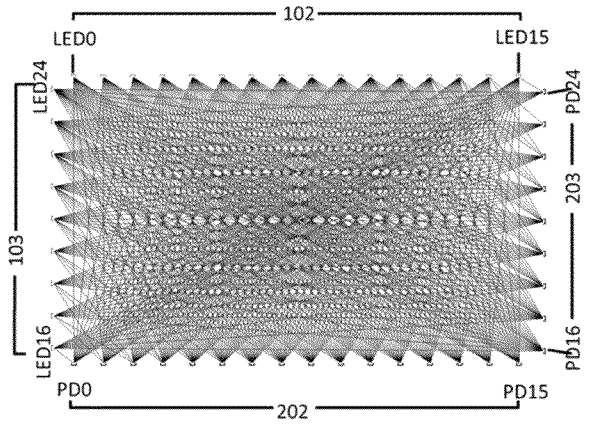
(74) *Attorney, Agent, or Firm* — Soquel Group LLC

(57) **ABSTRACT**

A lens for placement opposite a diode in an optical touch sensor, including an upper portion including an upper refractive surface located nearer to the diode, and an upper reflector located further from the diode, the upper reflector being curved in two dimensions and cut horizontally by a top horizontal plane of the lens, and a lower portion, coplanar with the diode, including a lower refractive surface located nearer to the diode, and a lower reflector located further from the diode, the lower reflector being curved in the two dimensions and cut horizontally by a bottom horizontal plane of the lens, wherein the upper and the lower reflector are symmetrical and vertically aligned, and wherein non-collimated light reflected by the lower reflector onto the upper reflector is partially collimated in the two dimensions by the lower reflector and further collimated in the two dimensions by the upper reflector.

11 Claims, 84 Drawing Sheets



Related U.S. Application Data

of application No. 12/371,609, filed on Feb. 15, 2009, now Pat. No. 8,339,379, and a continuation-in-part of application No. 12/760,567, filed on Apr. 15, 2010, and a continuation-in-part of application No. 12/760,568, filed on Apr. 15, 2010.

(60) Provisional application No. 61/169,779, filed on Apr. 16, 2009, provisional application No. 61/410,930, filed on Nov. 7, 2010, provisional application No. 61/380,600, filed on Sep. 7, 2010, provisional application No. 61/379,012, filed on Sep. 1, 2010, provisional application No. 61/950,868, filed on Mar. 11, 2014, provisional application No. 61/923,775, filed on Jan. 6, 2014, provisional application No. 61/833,161, filed on Jun. 10, 2013, provisional application No. 61/919,759, filed on Dec. 22, 2013, provisional application No. 61/911,915, filed on Dec. 4, 2013, provisional application No. 61/830,671, filed on Jun. 4, 2013.

(52) **U.S. Cl.**
CPC ***G06F 3/0425*** (2013.01); ***G06F 3/0428*** (2013.01); *G06F 2203/04102* (2013.01); *G06F 2203/04104* (2013.01); *G06F 2203/04109* (2013.01); ***G06F 3/03547*** (2013.01)

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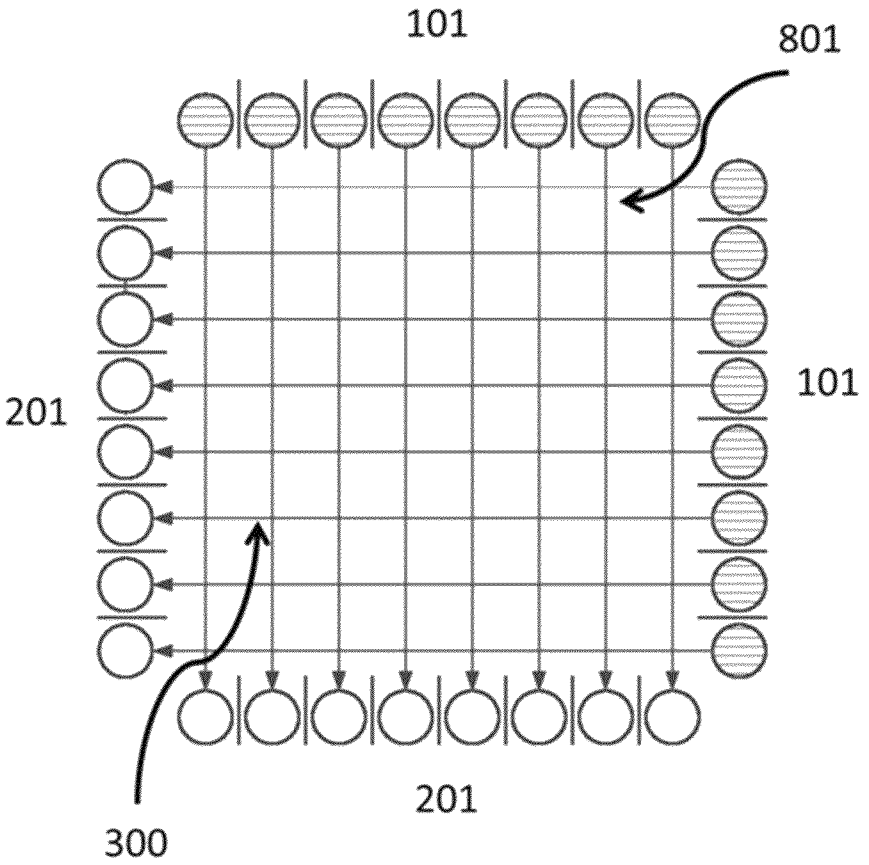

FIG. 1
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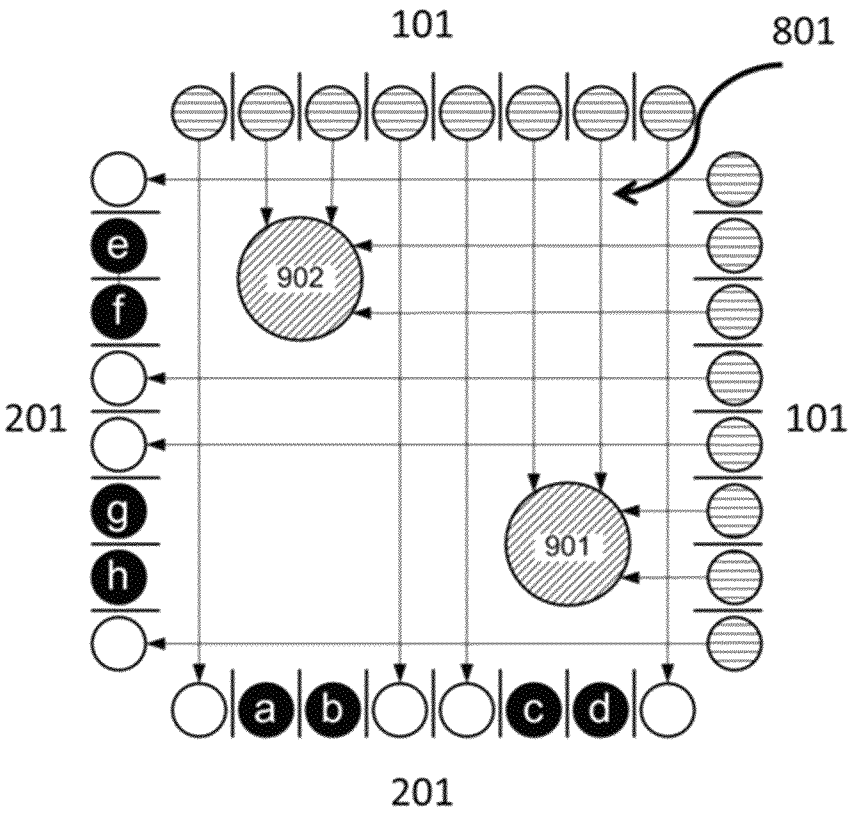

FIG. 2
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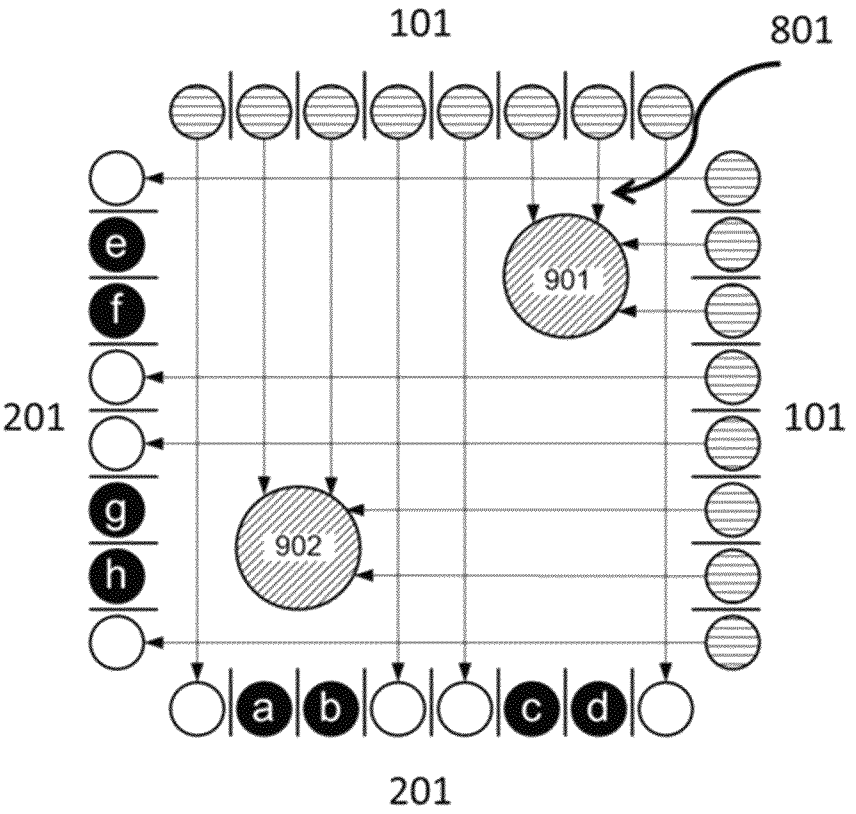

FIG. 3
(PRIOR ART)

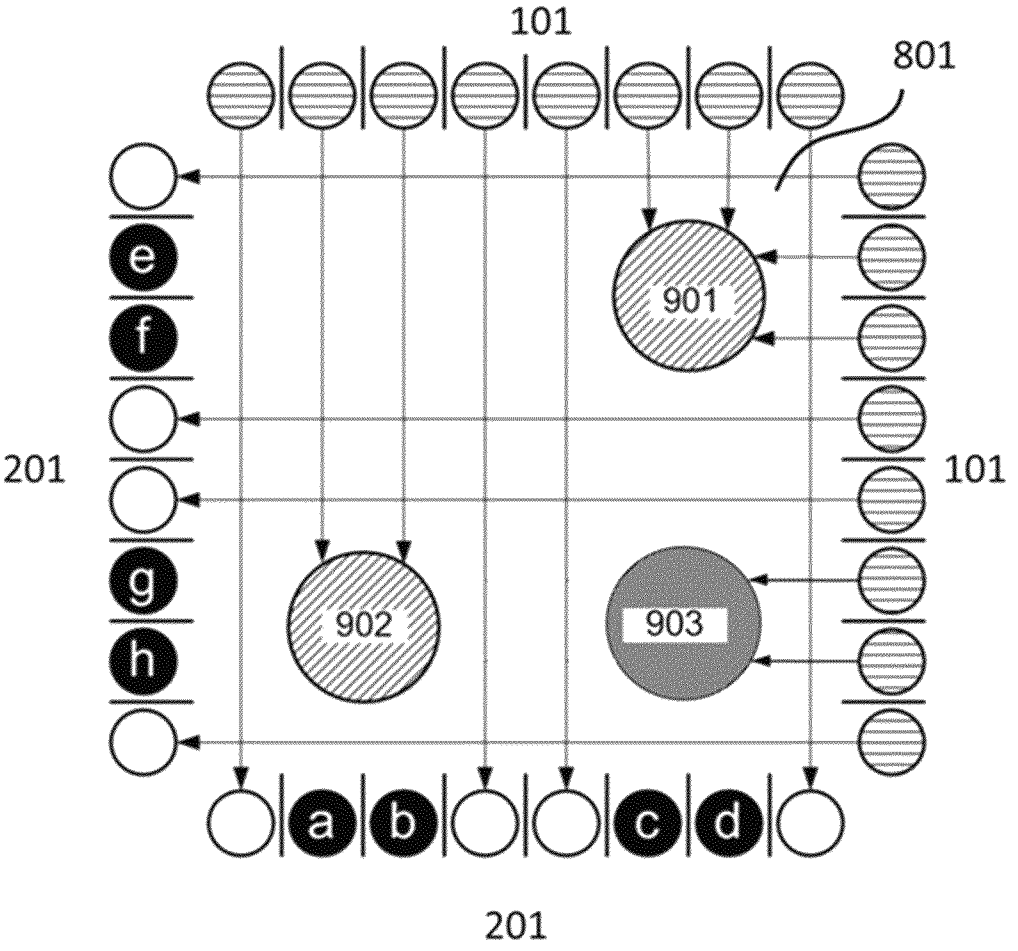

FIG. 4
(PRIOR ART)

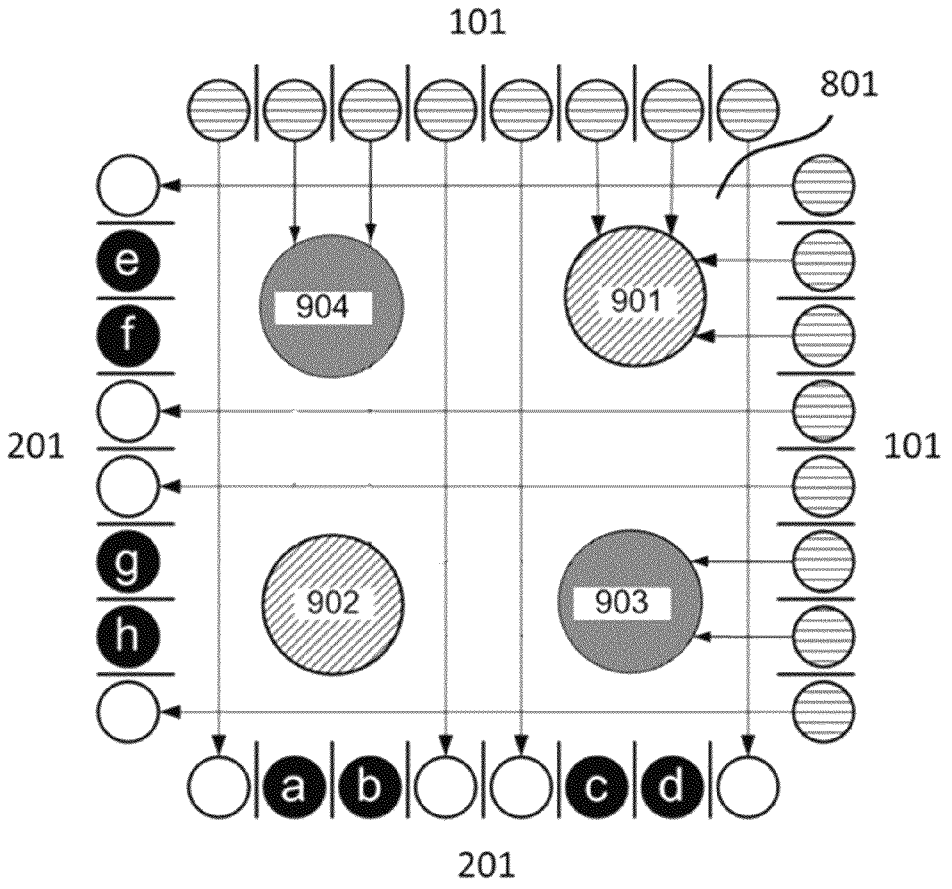

FIG. 5
(PRIOR ART)

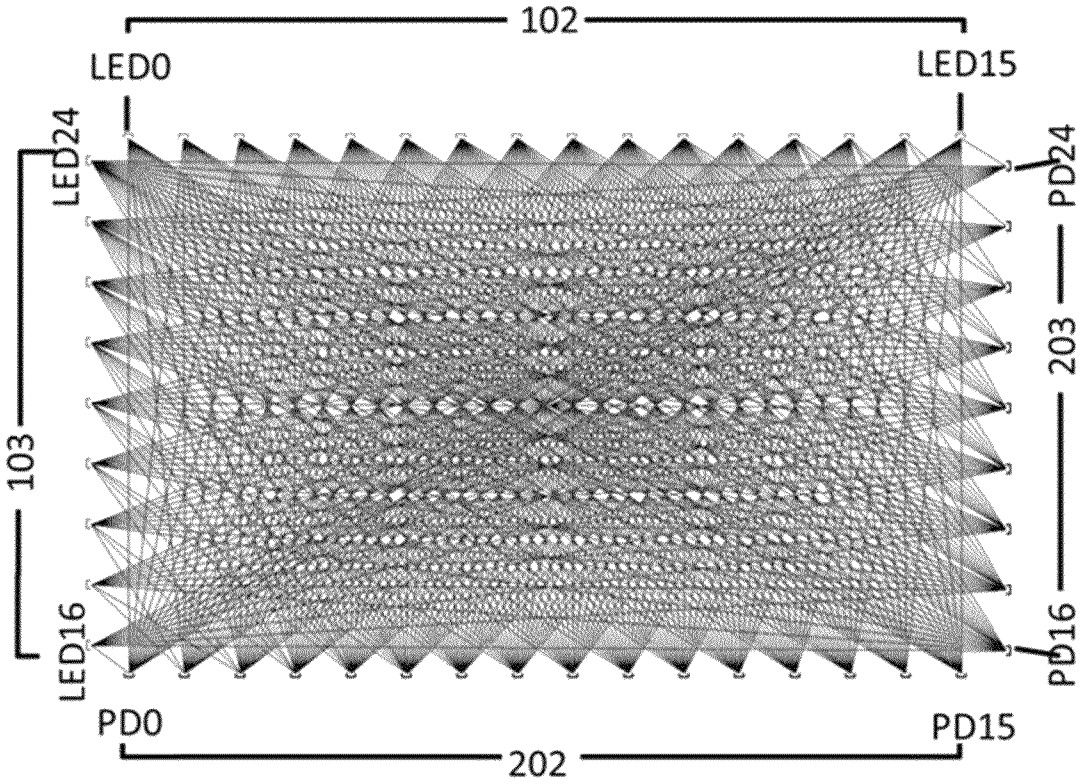

FIG. 6

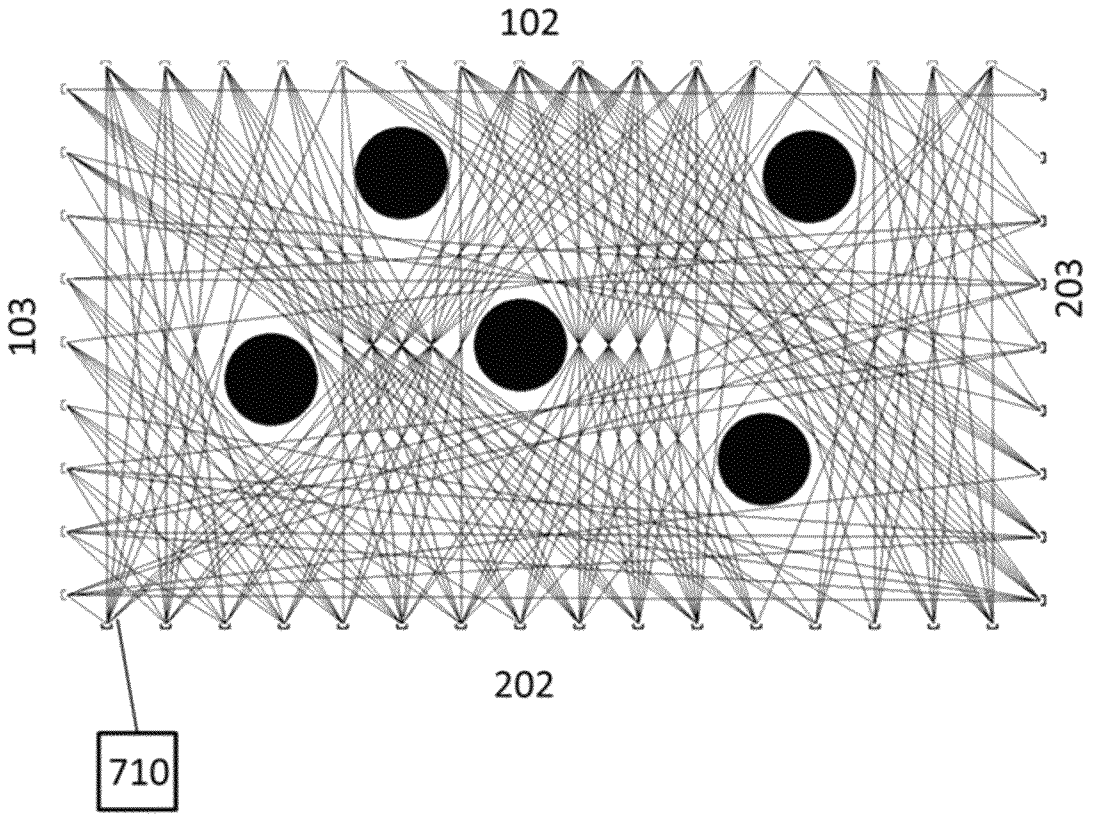

FIG. 7

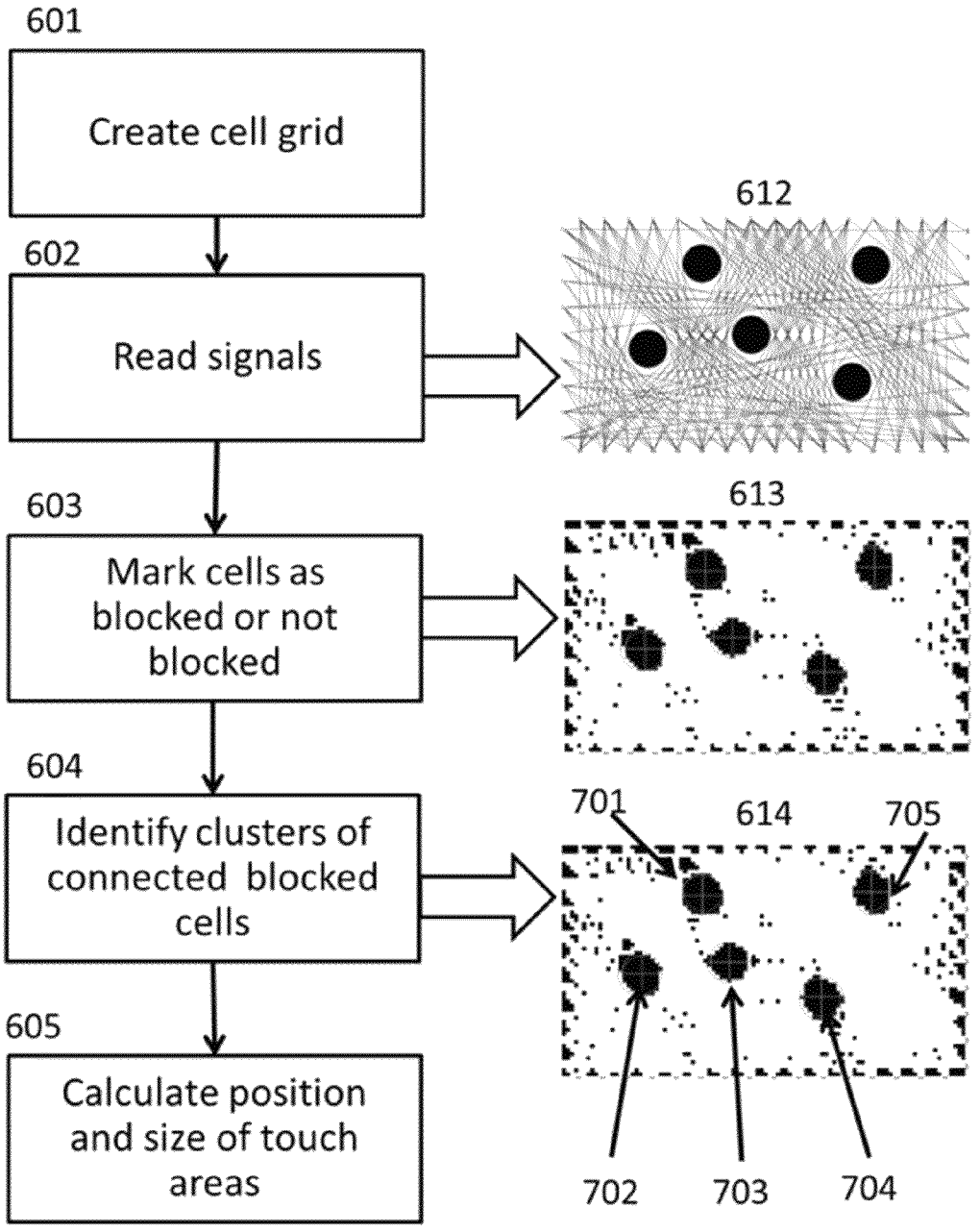
601
Create cell grid
602
Read signals
603
Mark cells as blocked or not blocked
604
Identify clusters of connected blocked cells
605
Calculate position and size of touch areas
612
613
701
614
705
702
703
704

FIG. 8

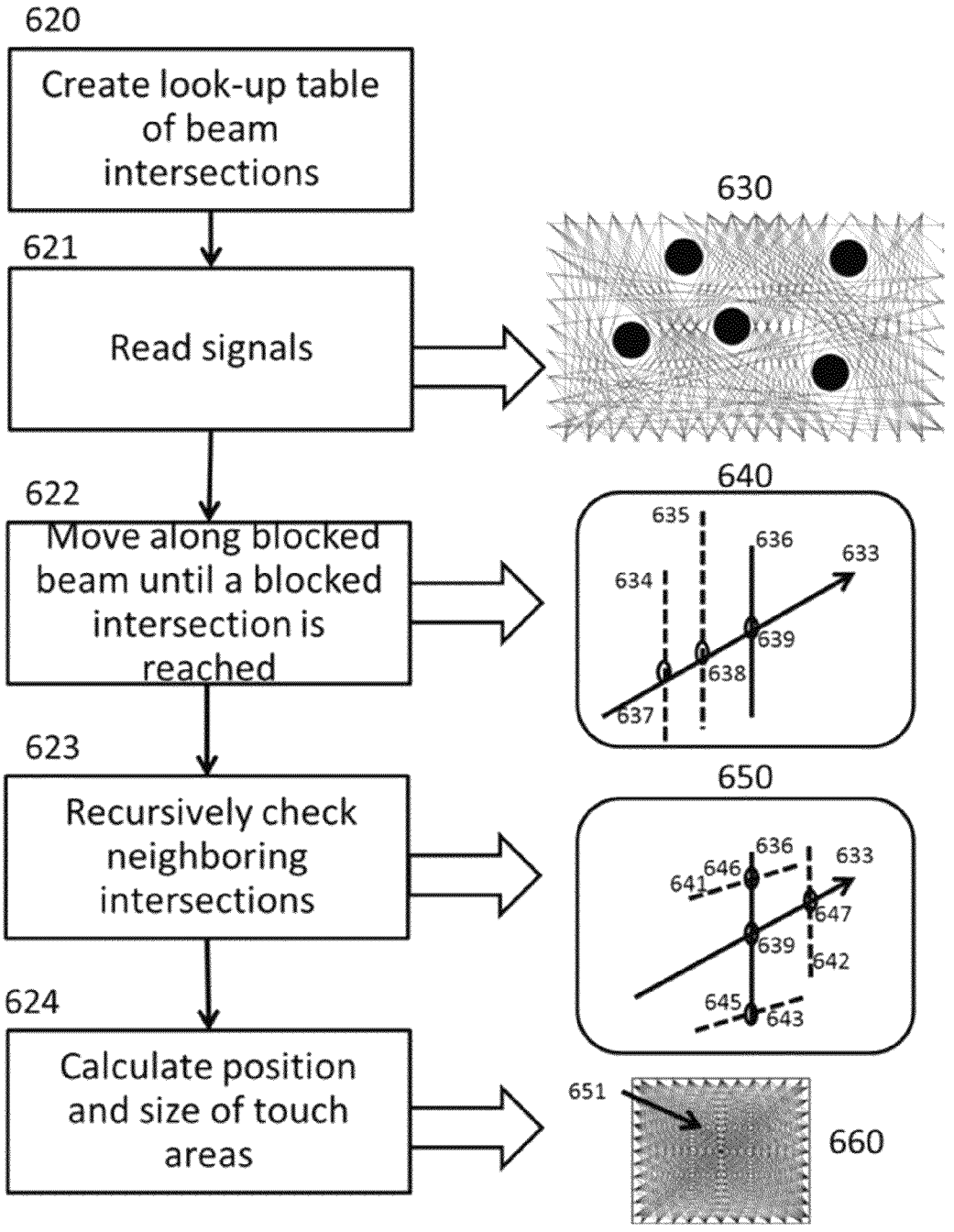
620
Create look-up table of beam intersections
621
Read signals
630
622
Move along blocked beam until a blocked intersection is reached
640
635
636
633
634
639
638
637
623
Recursively check neighboring intersections
650
636
633
641
646
647
639
642
645
643
624
Calculate position and size of touch areas
651
660

FIG. 9

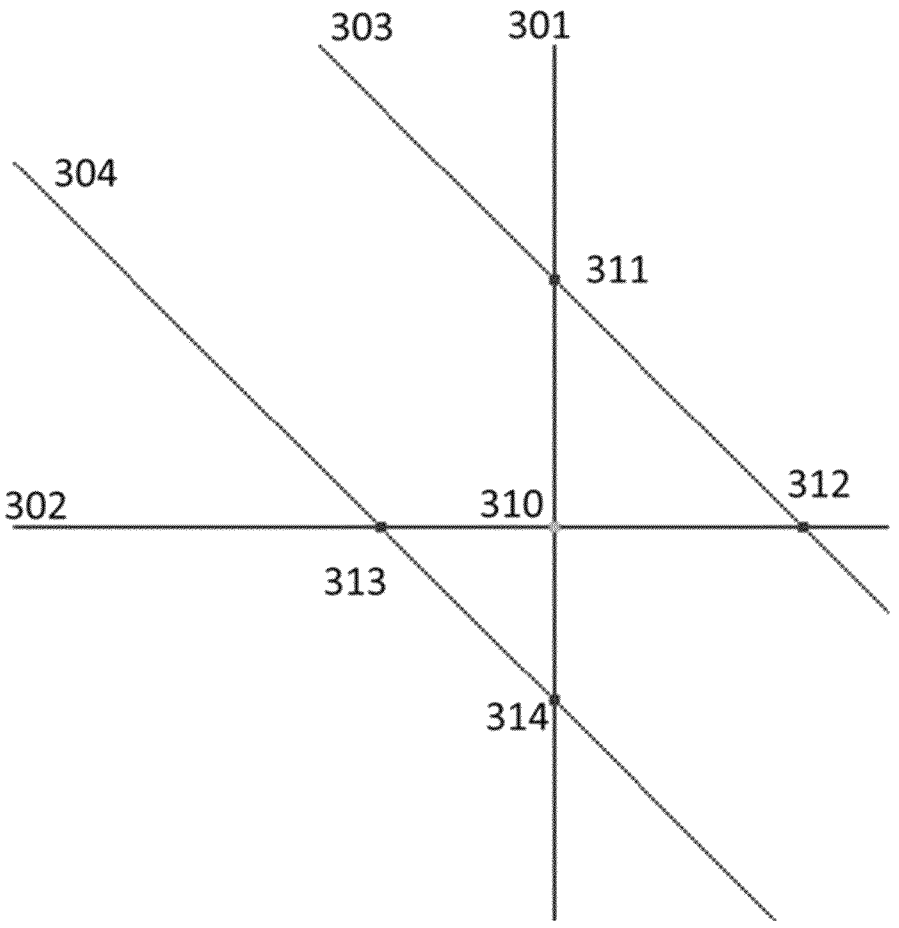

FIG. 10

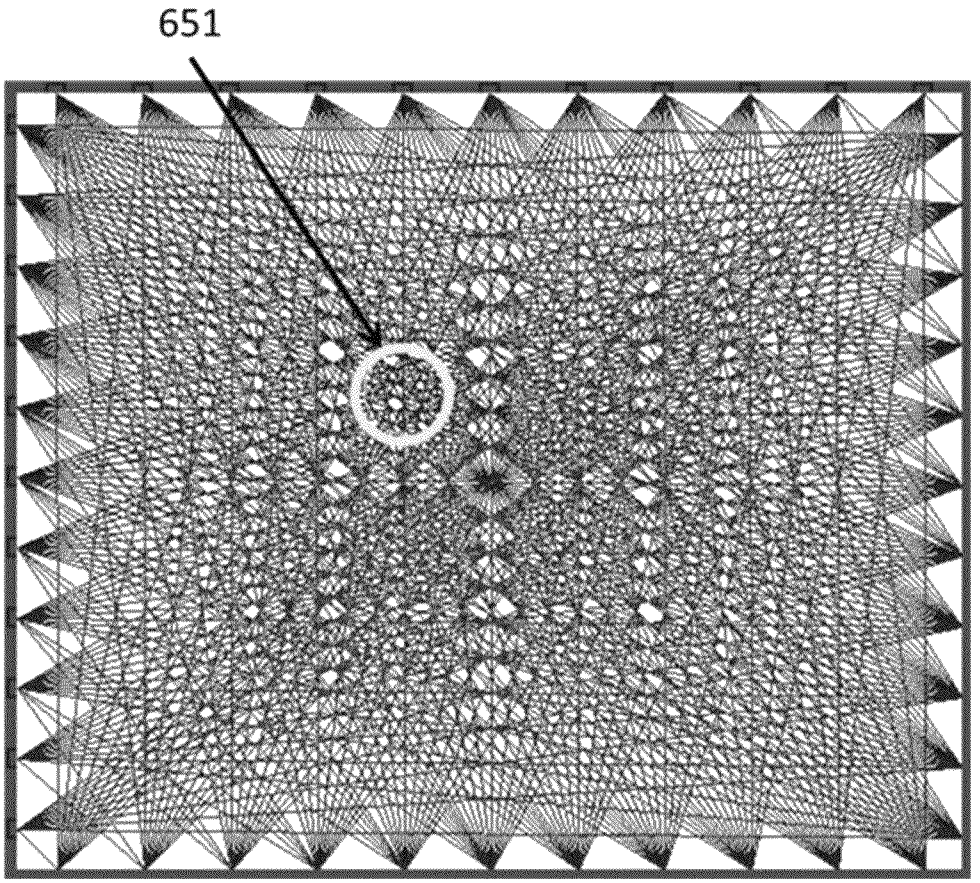

FIG. 11

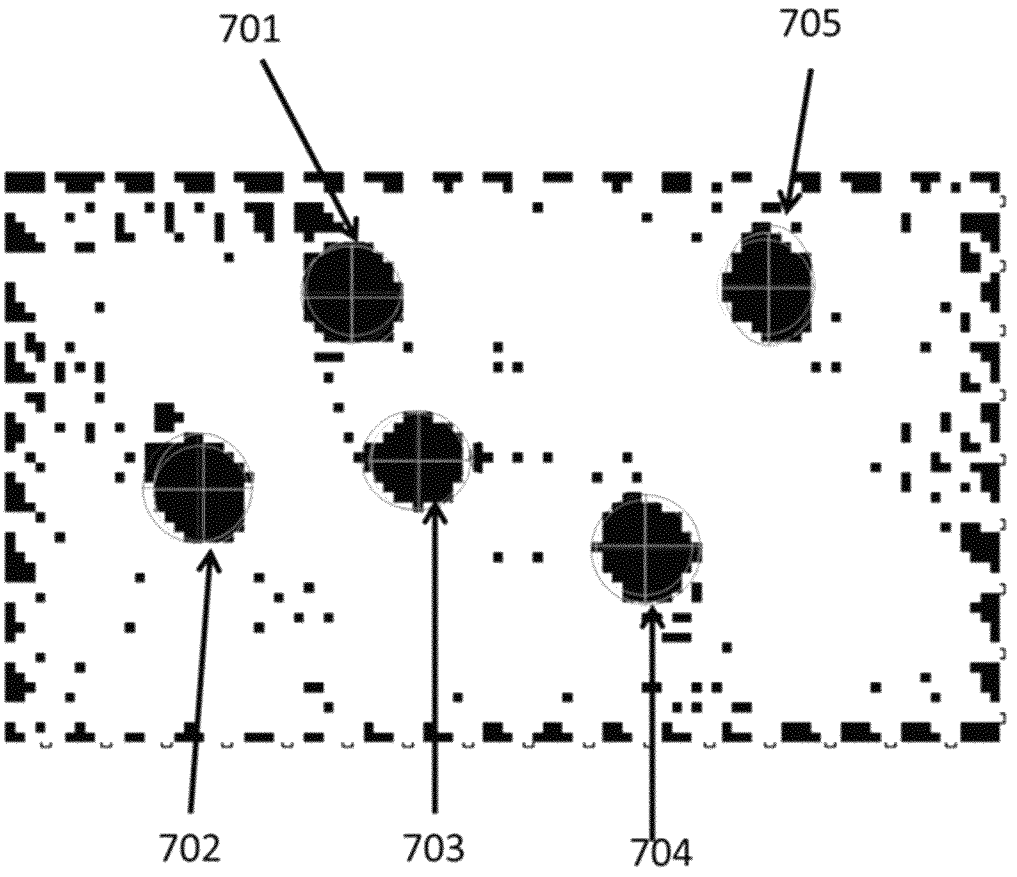

FIG. 12

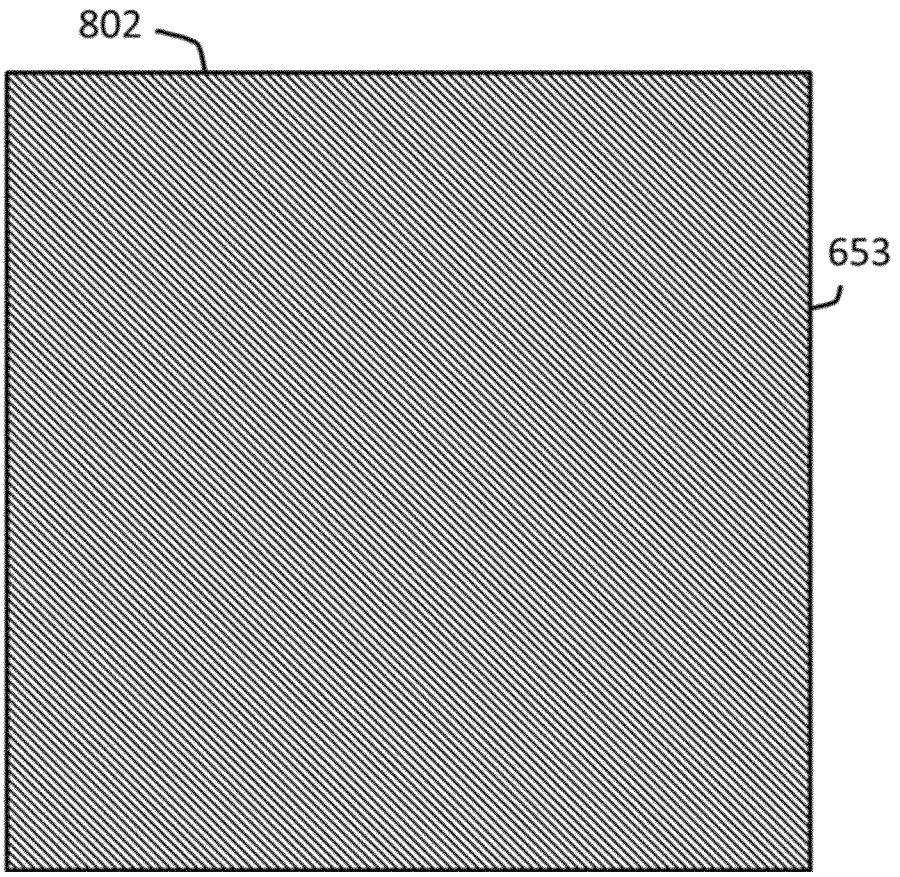

FIG. 13

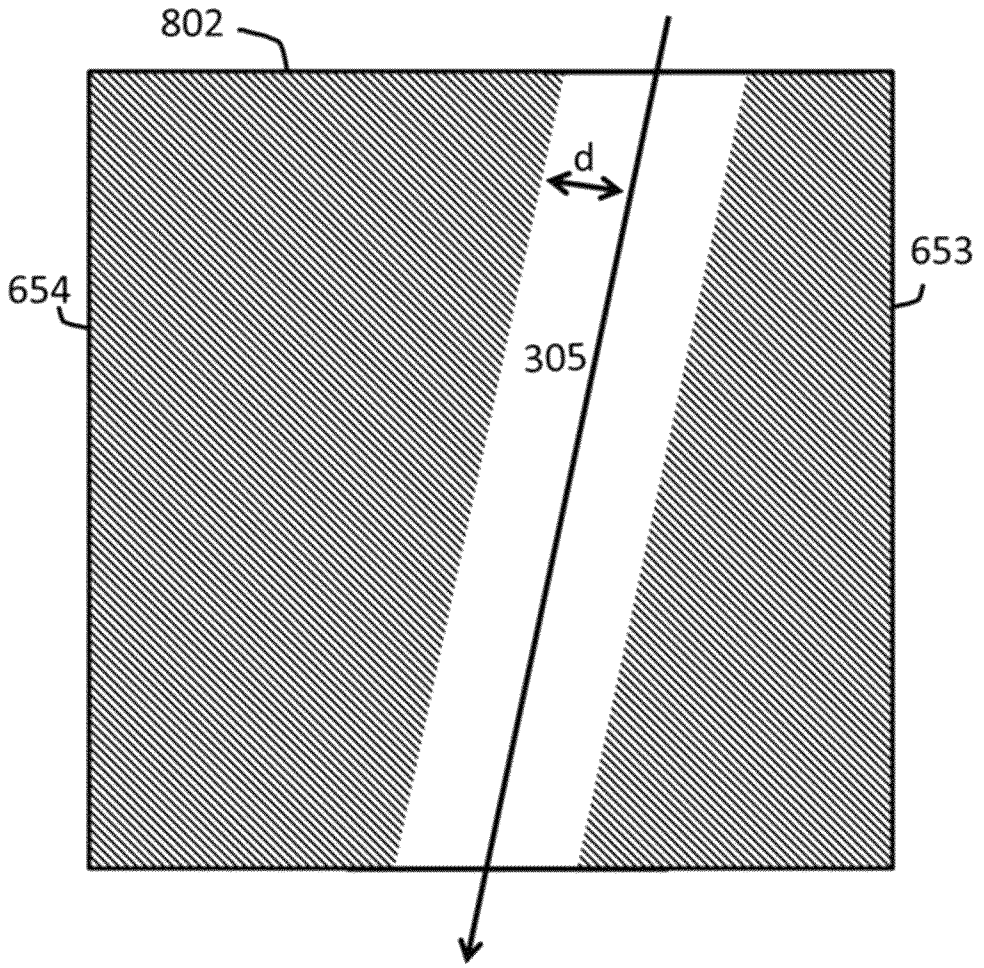

FIG. 14

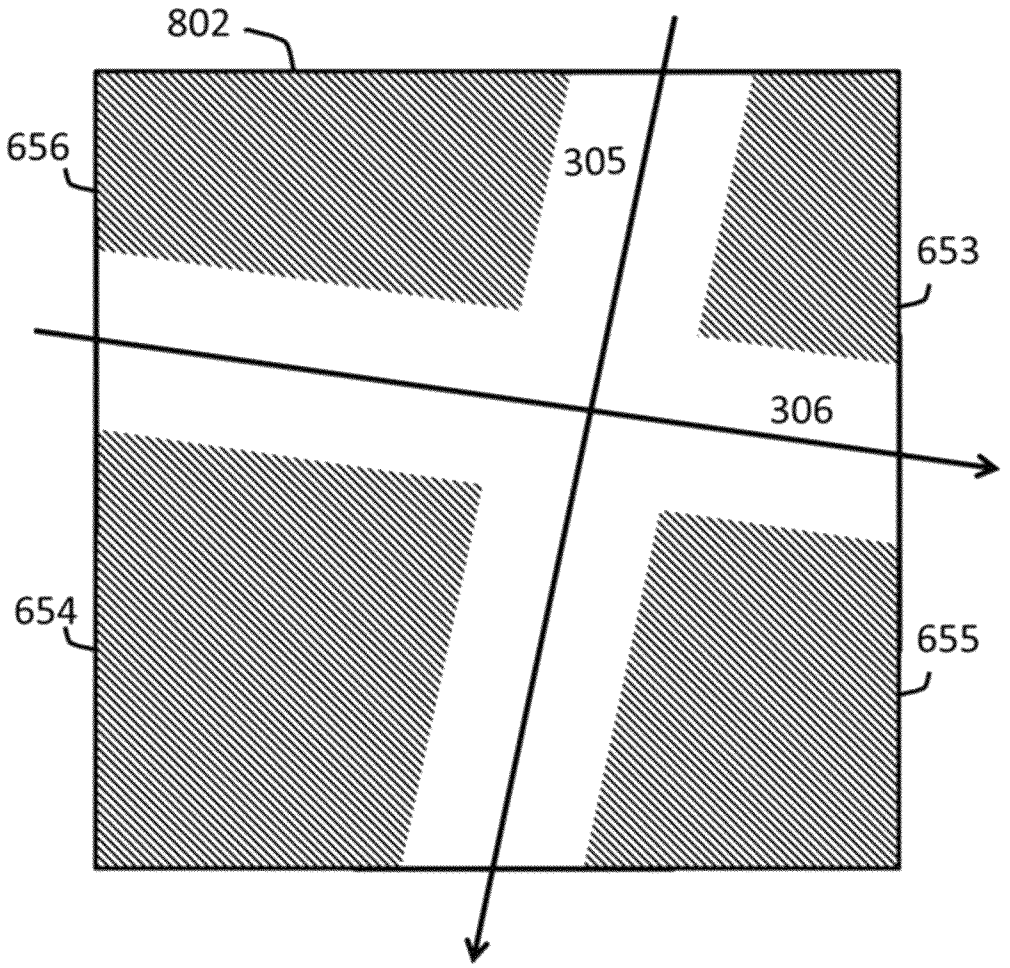

FIG. 15

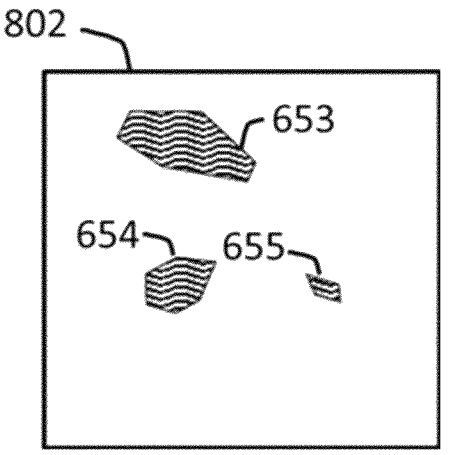

FIG. 16

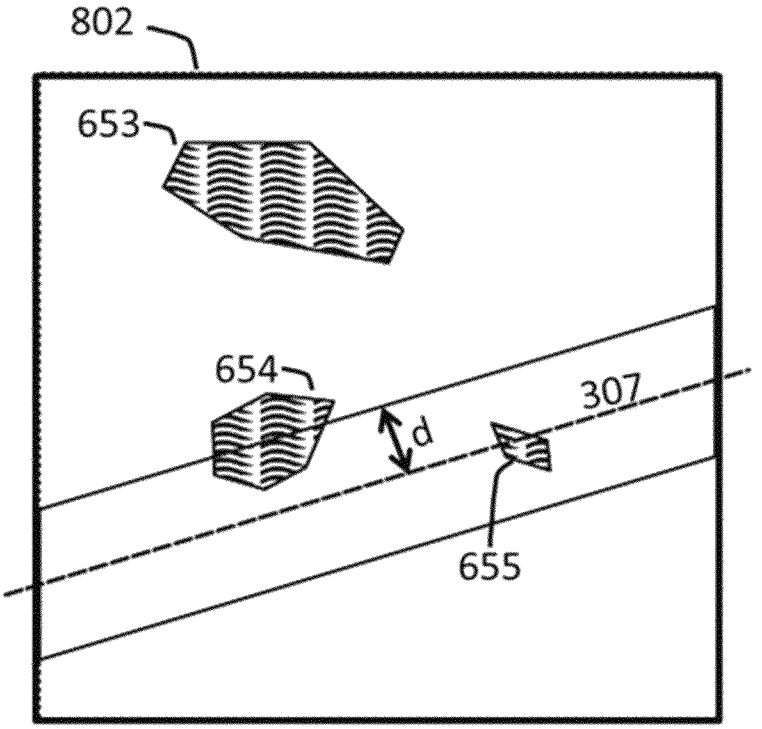

FIG. 17

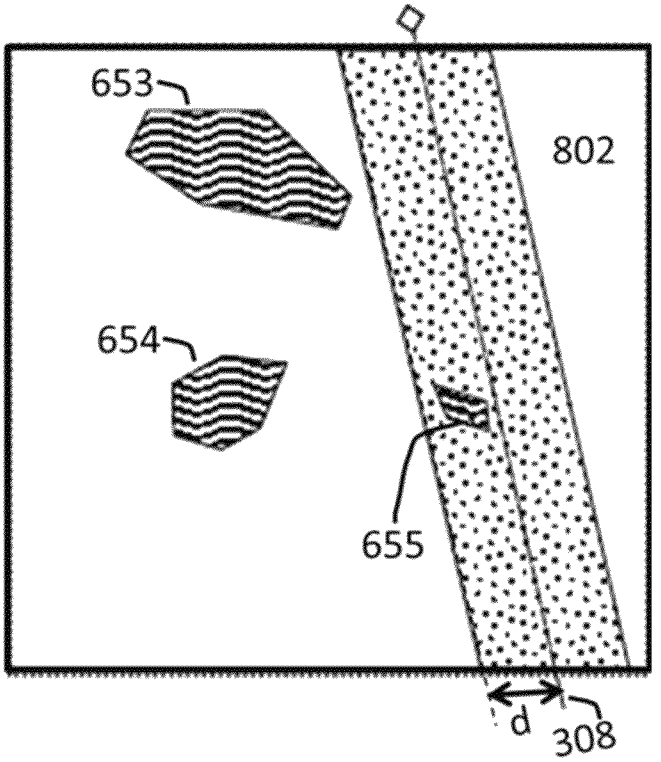

FIG. 18

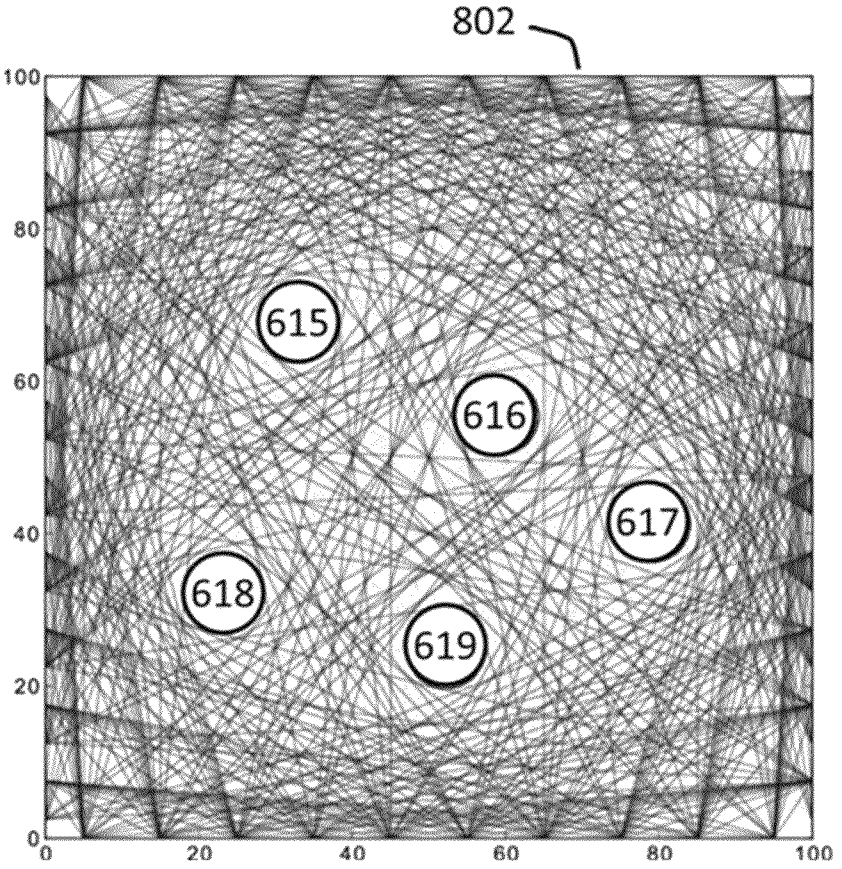

FIG. 19

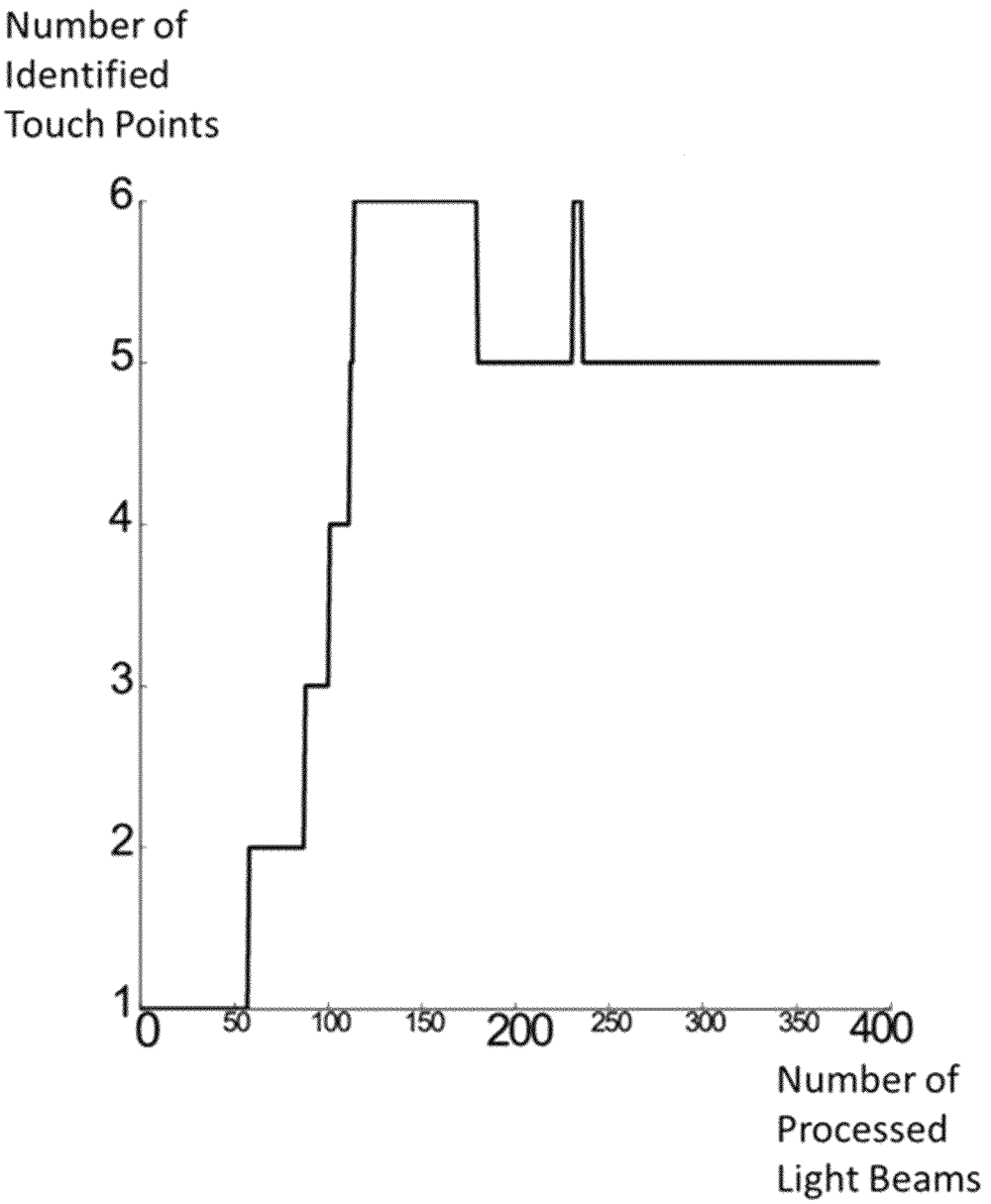
Number of
Identified
Touch Points
6
5
4
3
2
1
0
50
100
150
200
250
300
350
400
Number of
Processed
Light Beams

FIG. 20

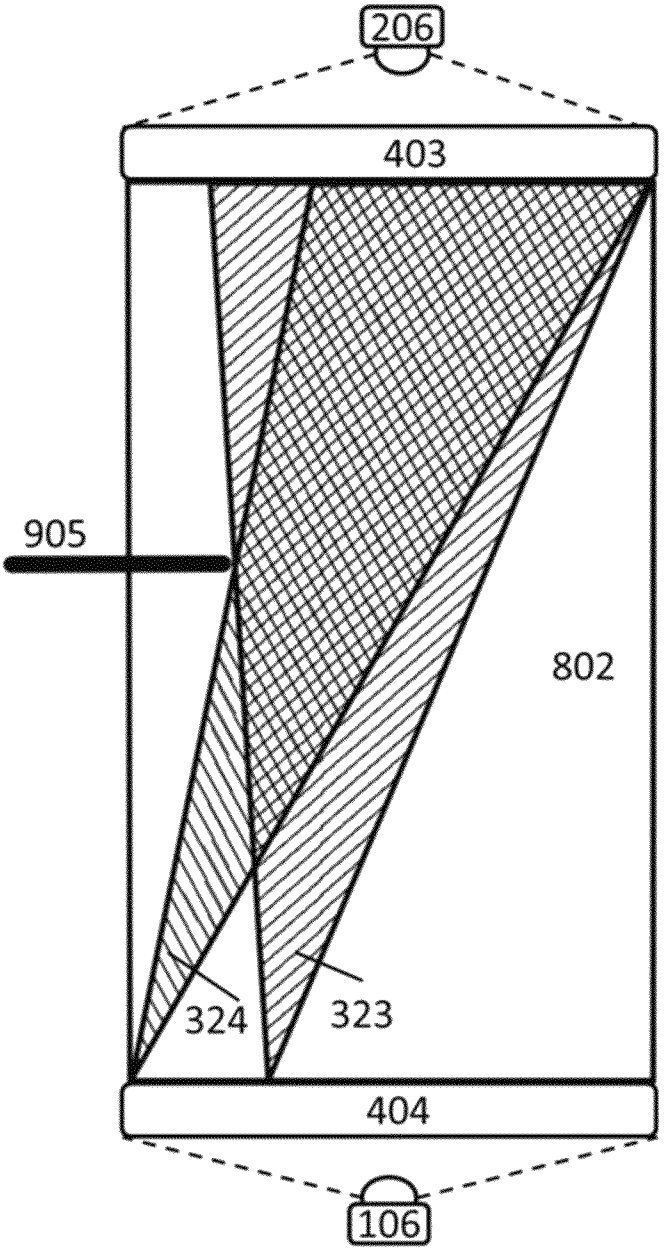

FIG. 21

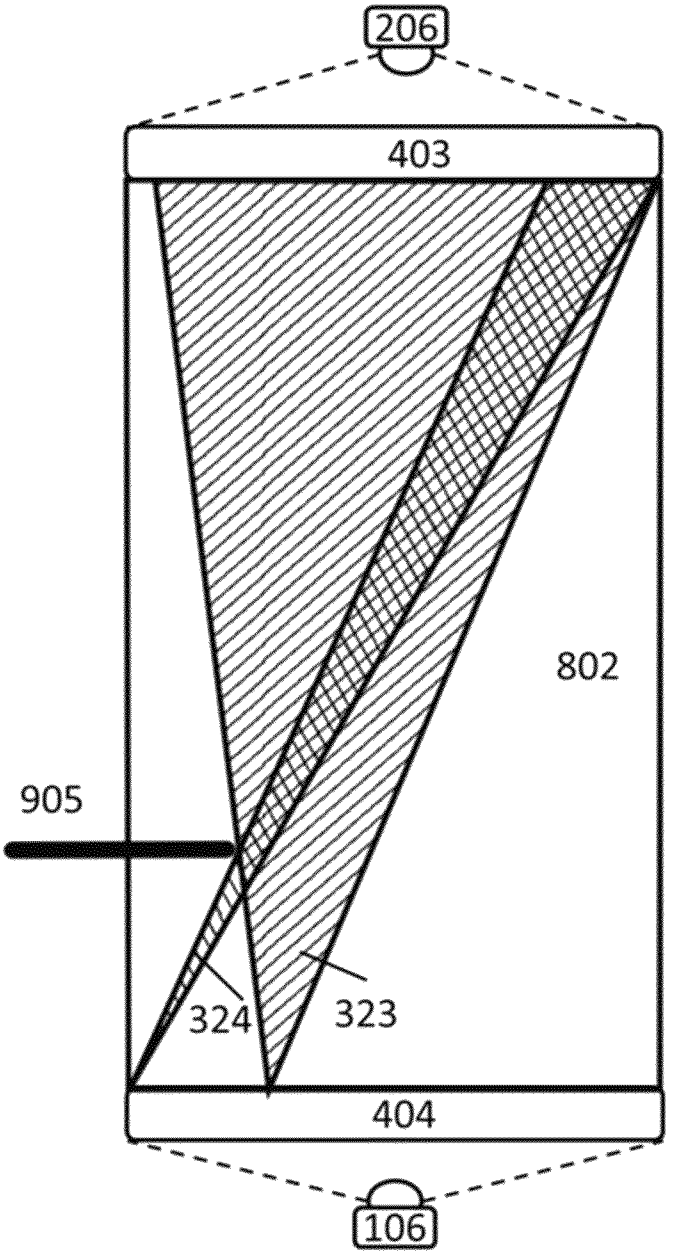

FIG. 22

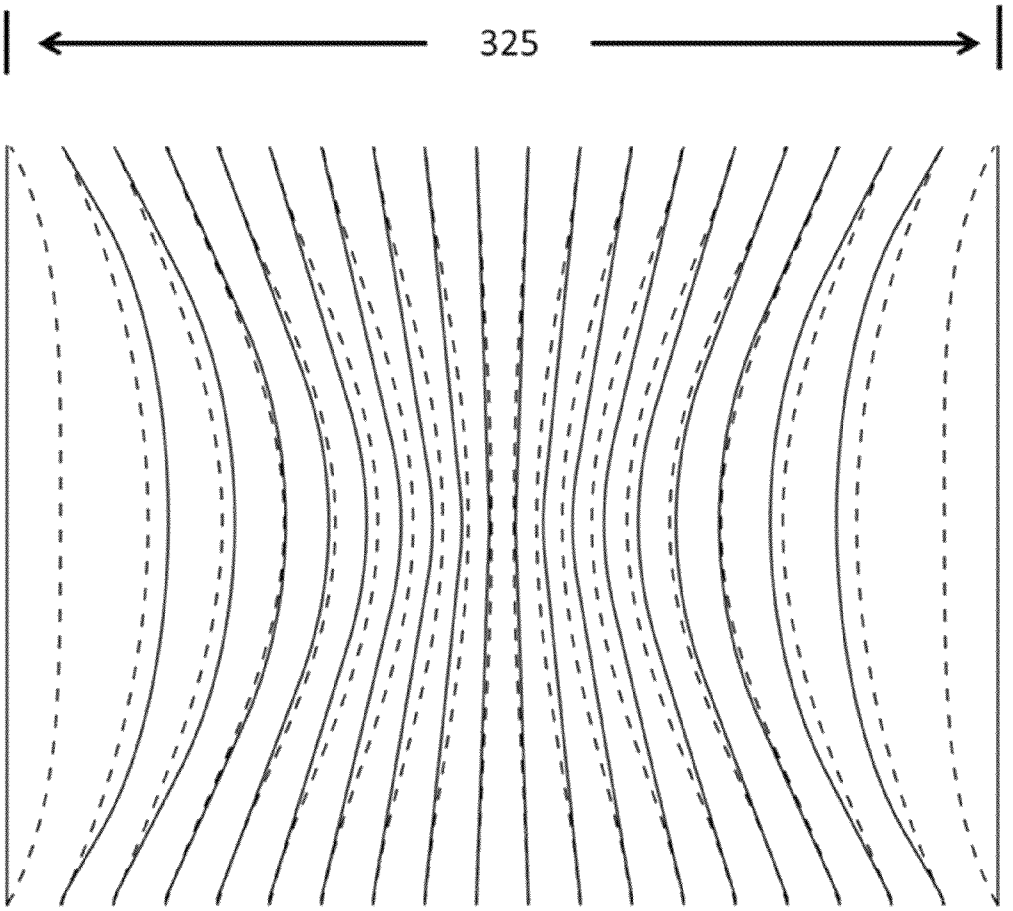

FIG. 23

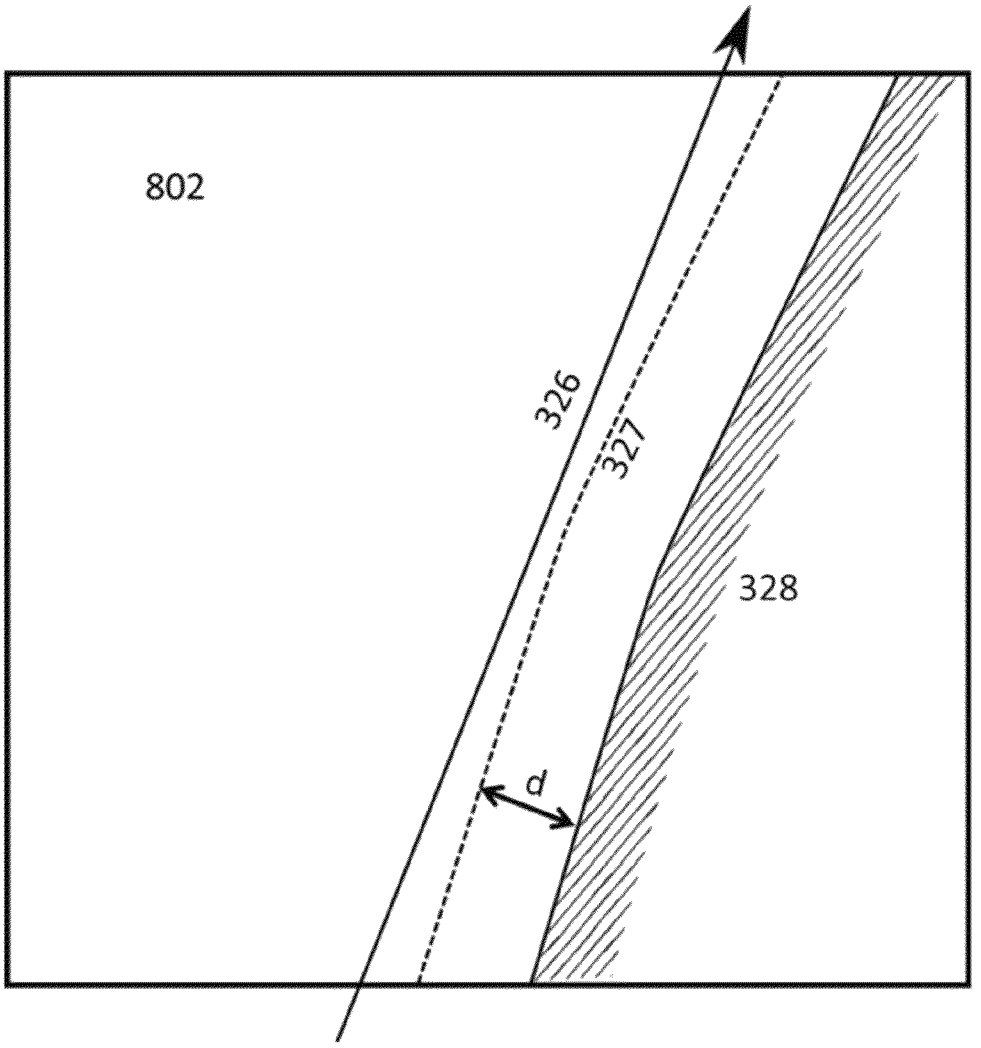

FIG. 24

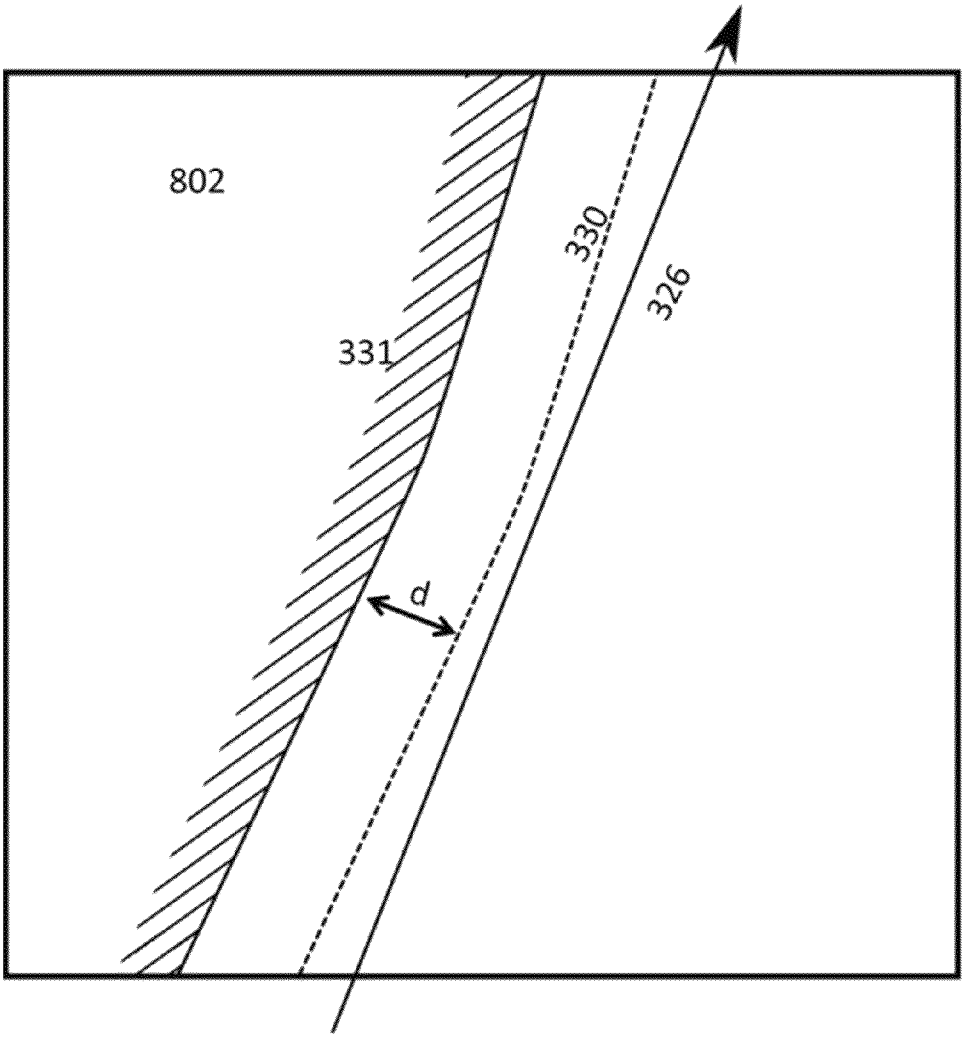

FIG. 25

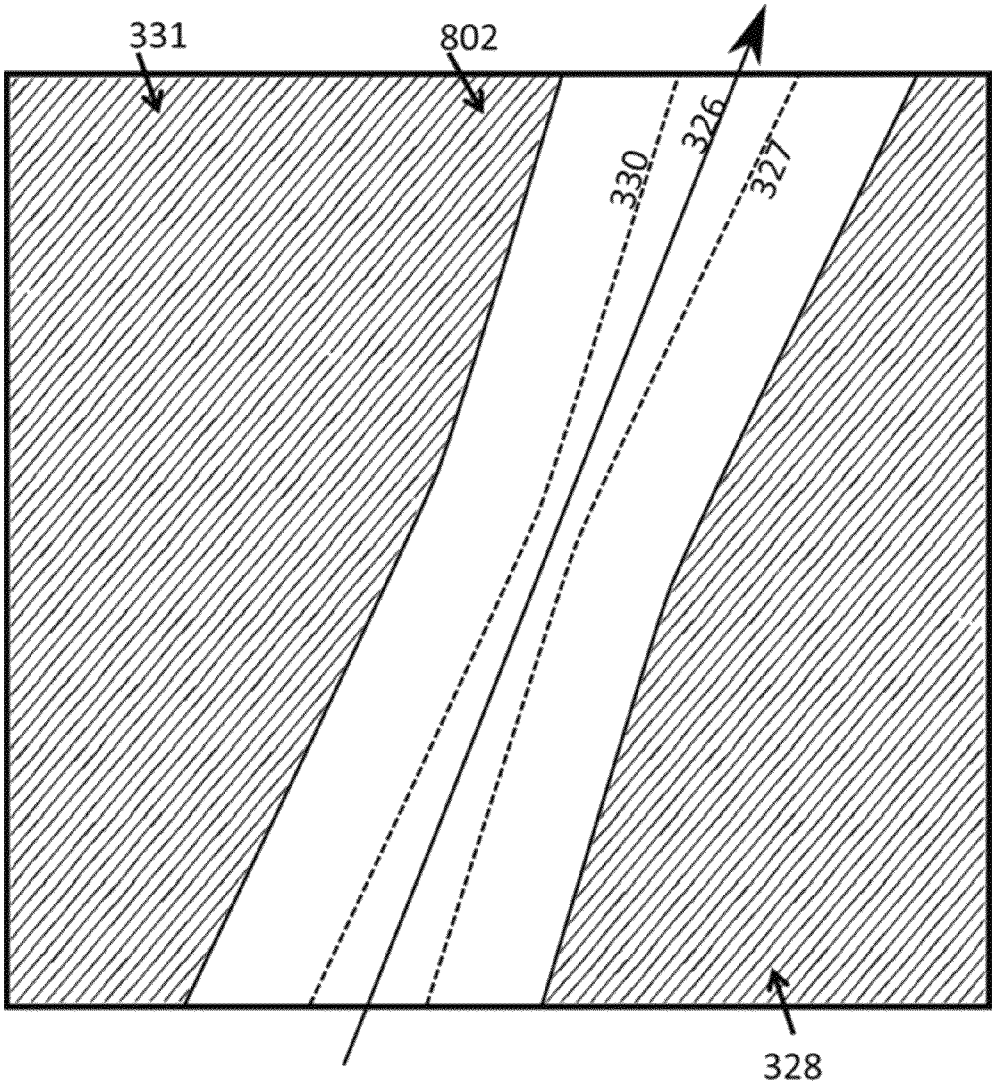

FIG. 26

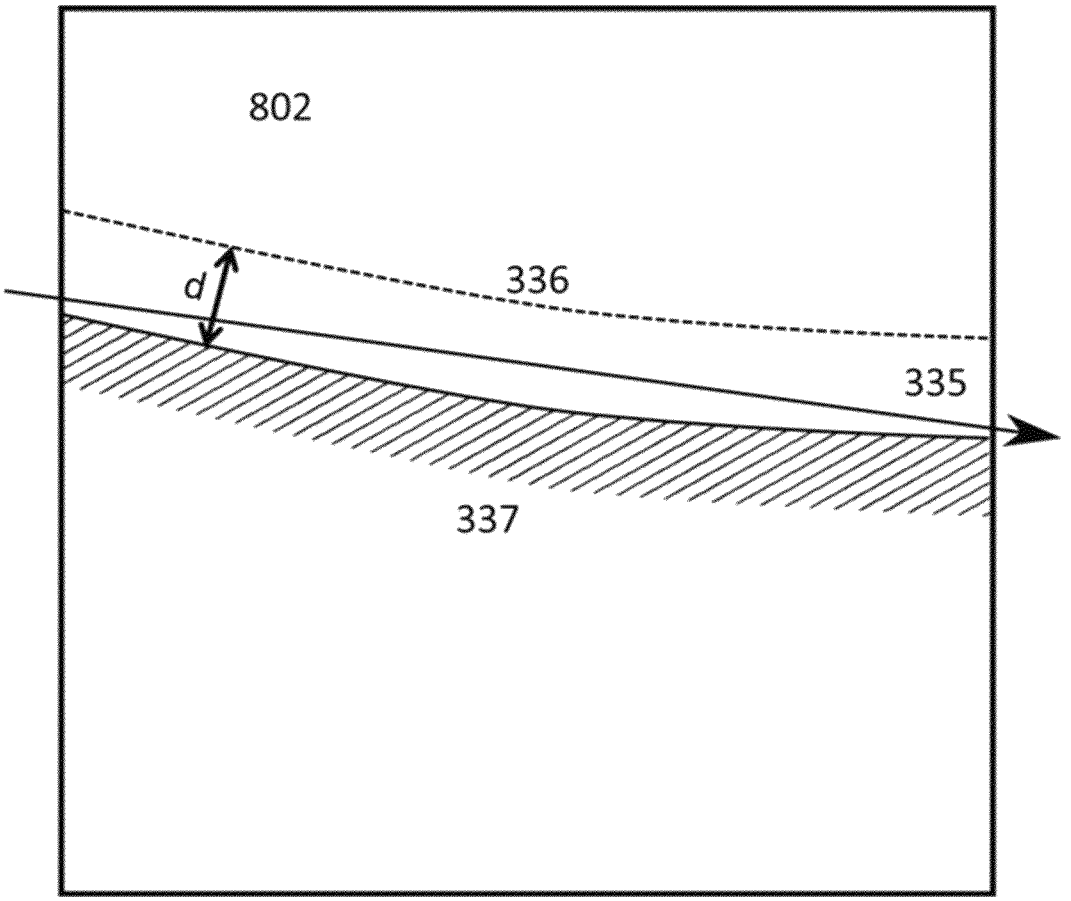

FIG. 27

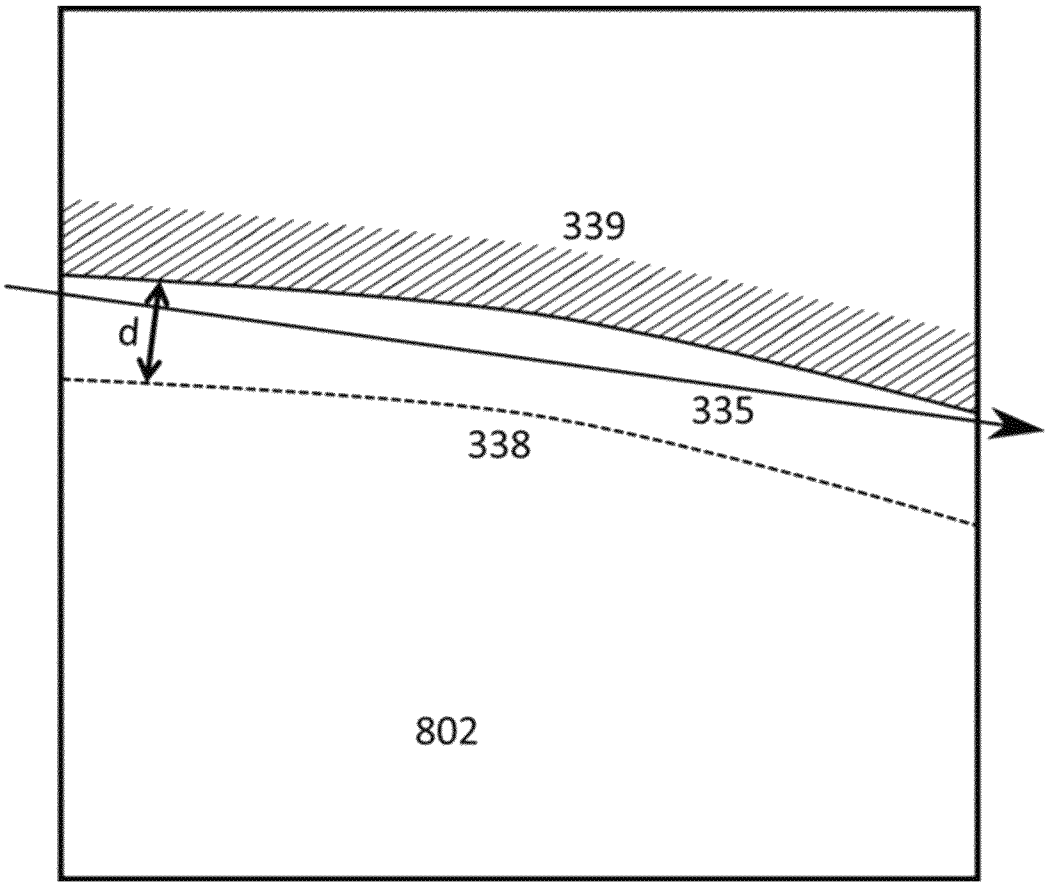

FIG. 28

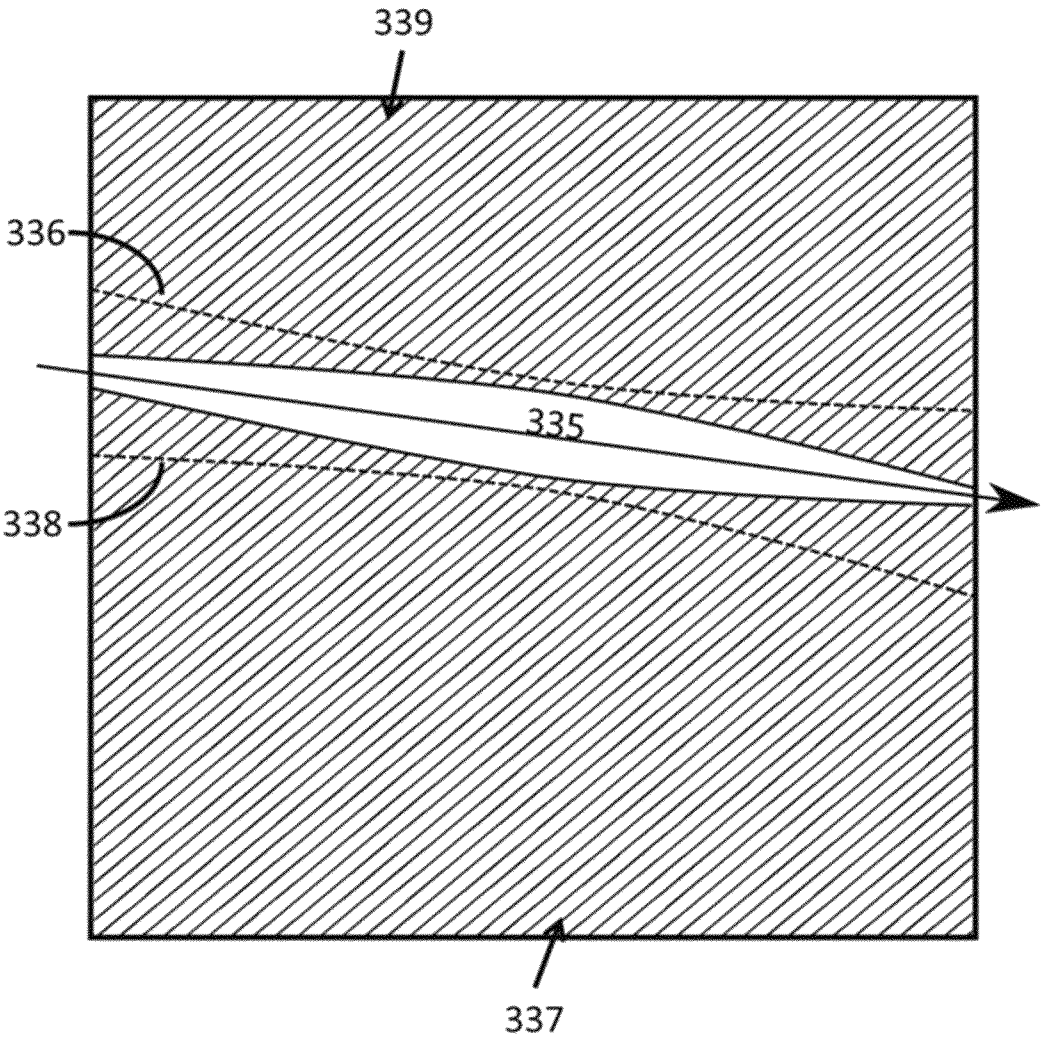

FIG. 29

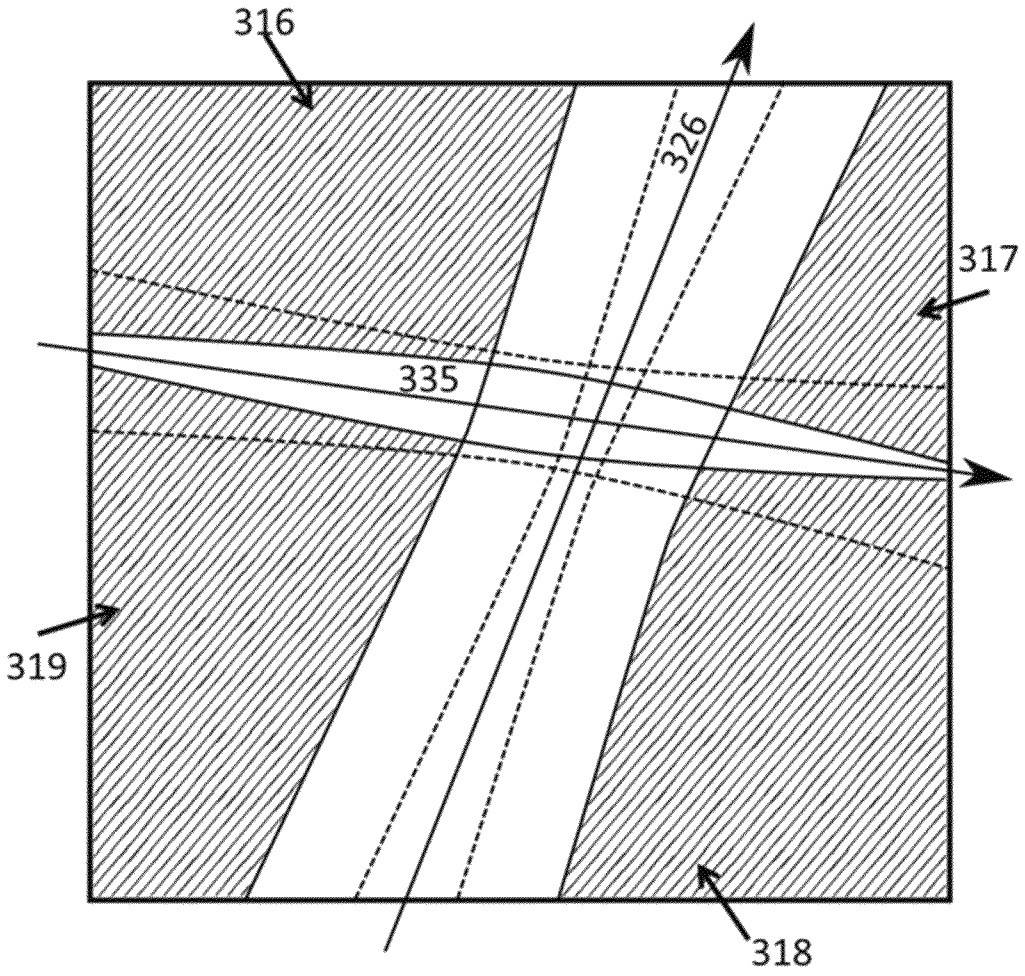

FIG. 30

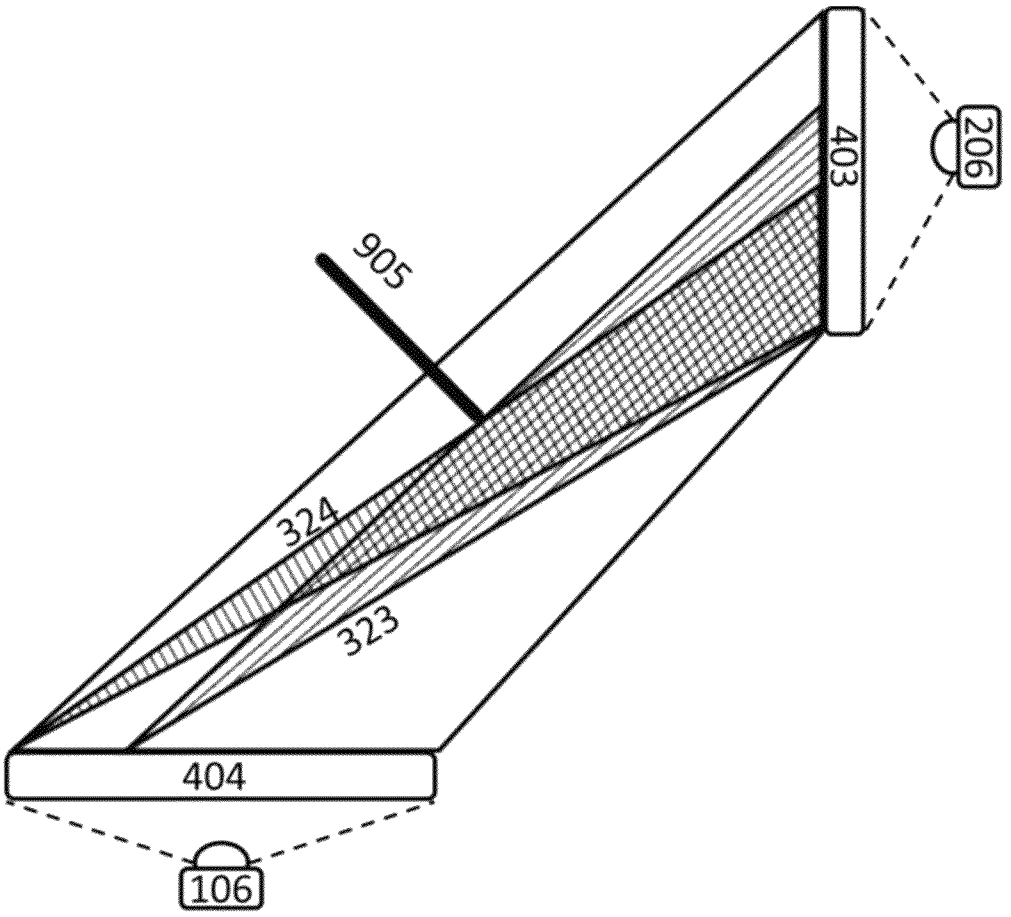

FIG. 31

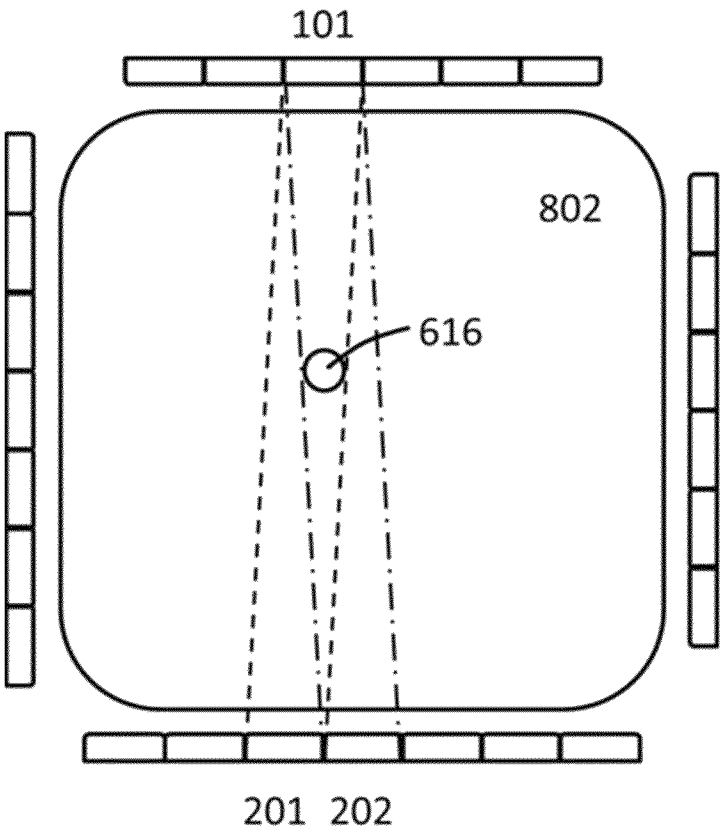

FIG. 32

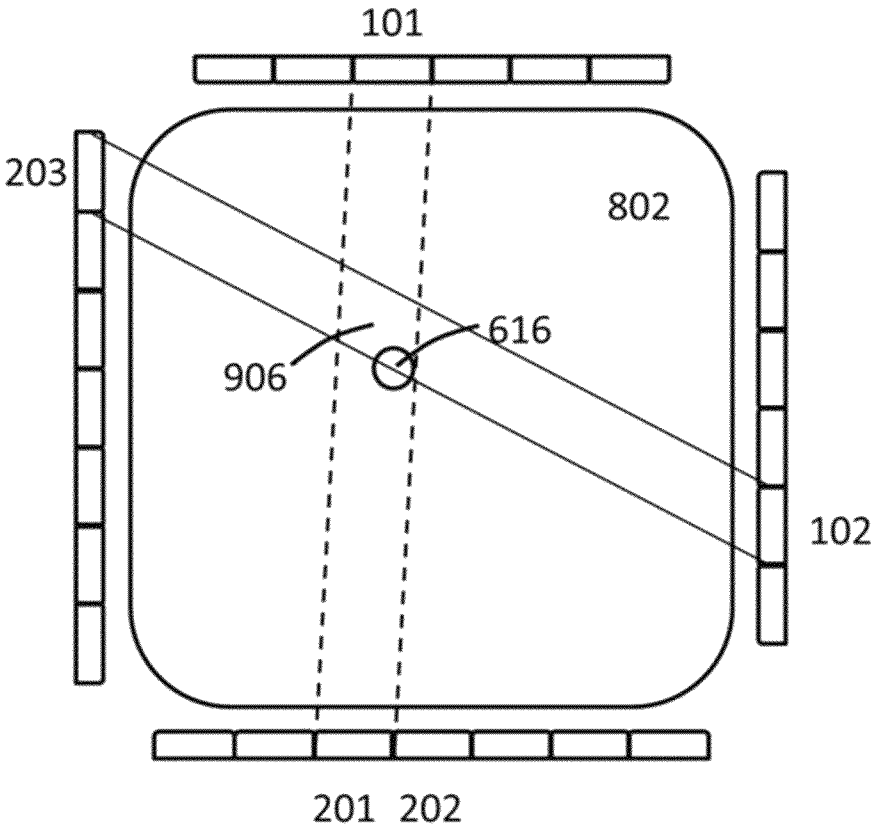

FIG. 33

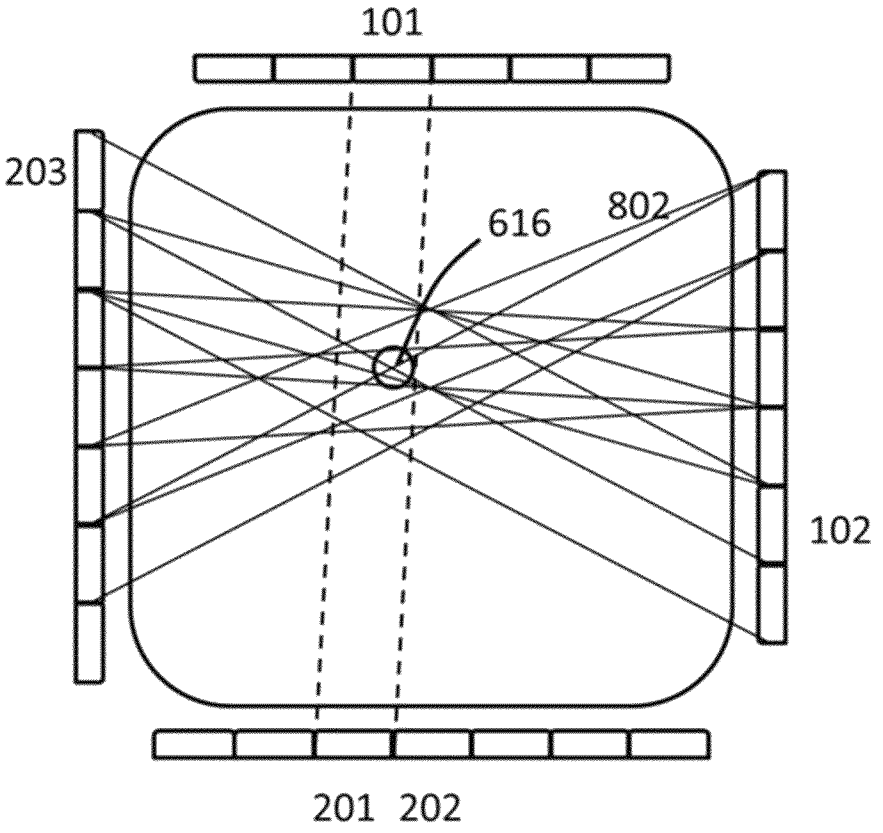

FIG. 34

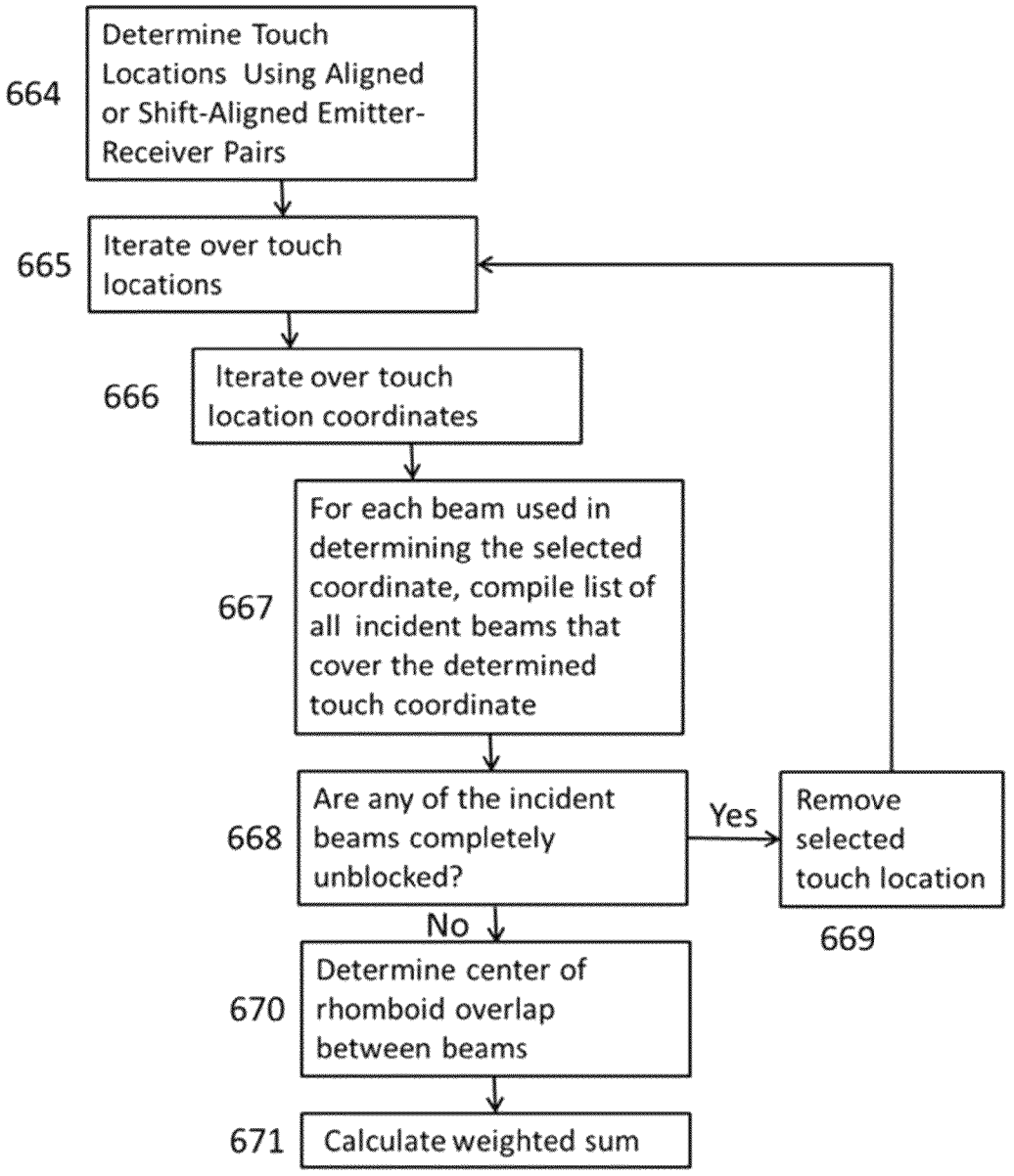
664
Determine Touch Locations Using Aligned or Shift-Aligned Emitter-Receiver Pairs
665
Iterate over touch locations
666
Iterate over touch location coordinates
667
For each beam used in determining the selected coordinate, compile list of all incident beams that cover the determined touch coordinate
668
Are any of the incident beams completely unblocked?
Yes
Remove selected touch location
669
No
670
Determine center of rhomboid overlap between beams
671
Calculate weighted sum

FIG. 35

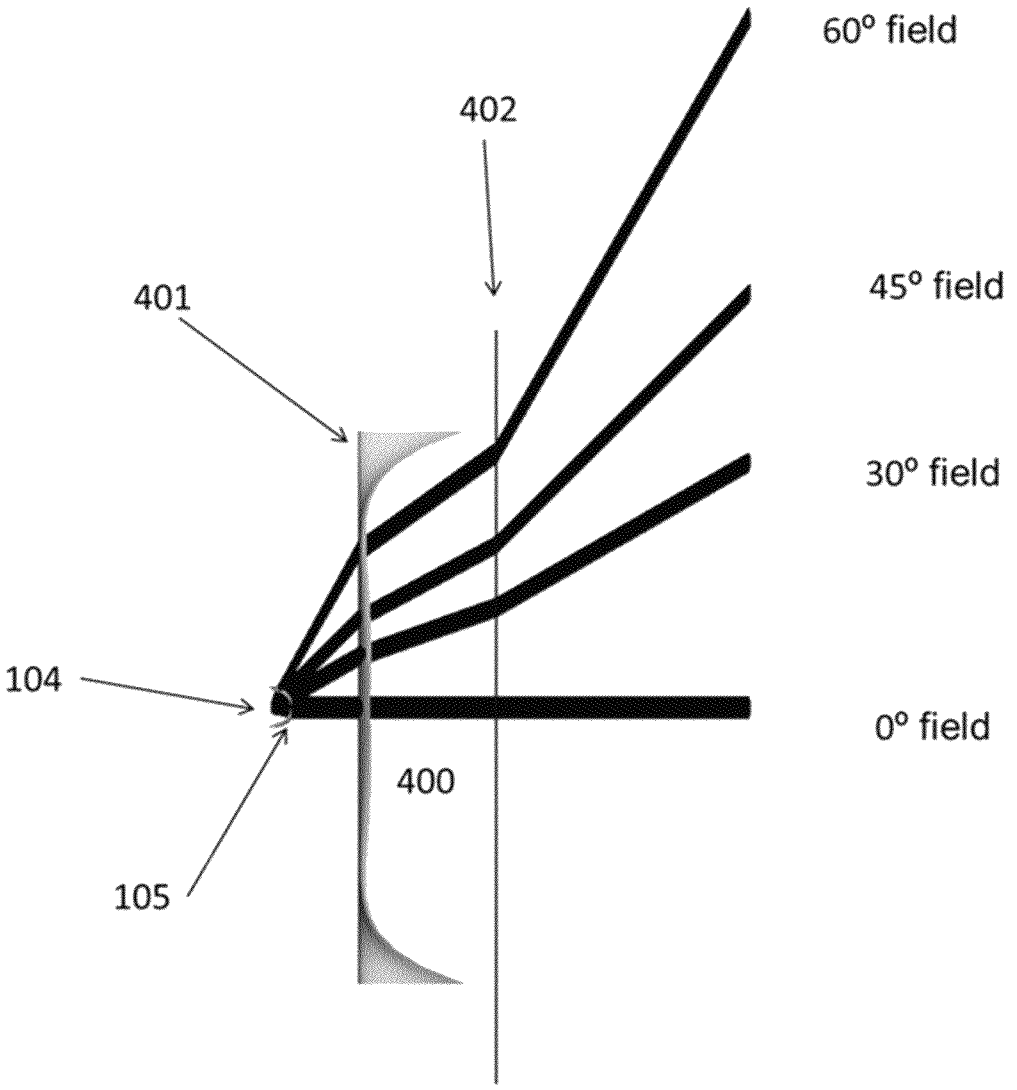

FIG. 36

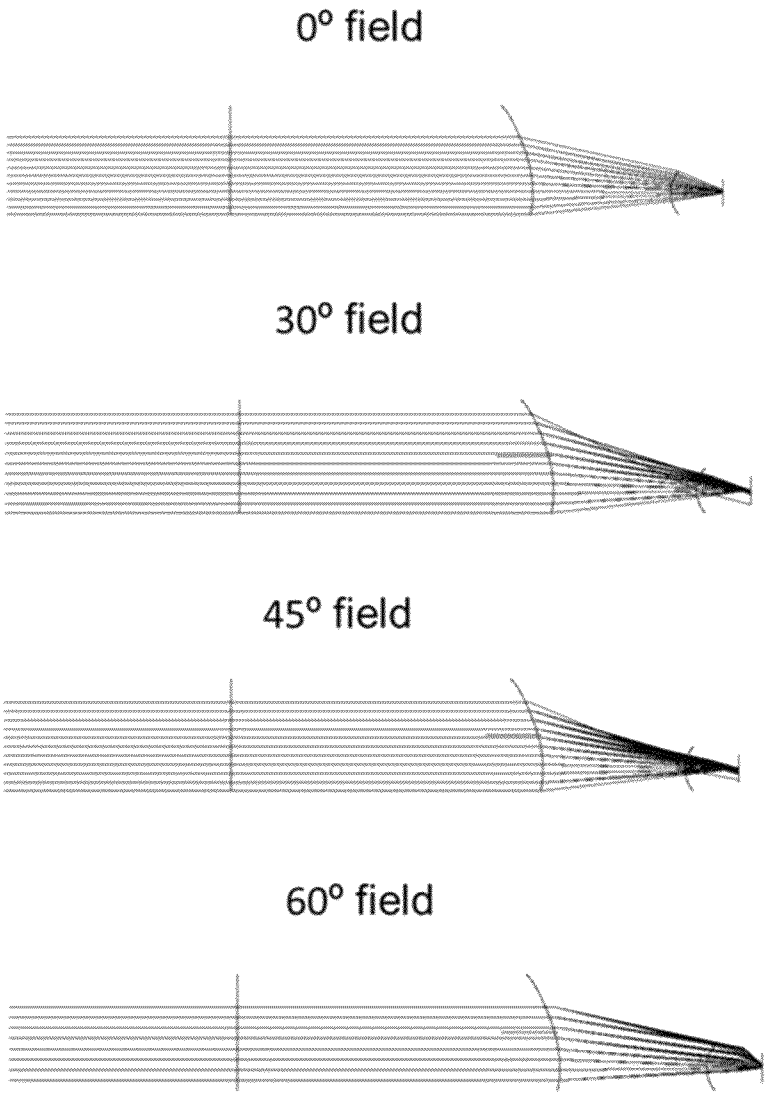

FIG. 37

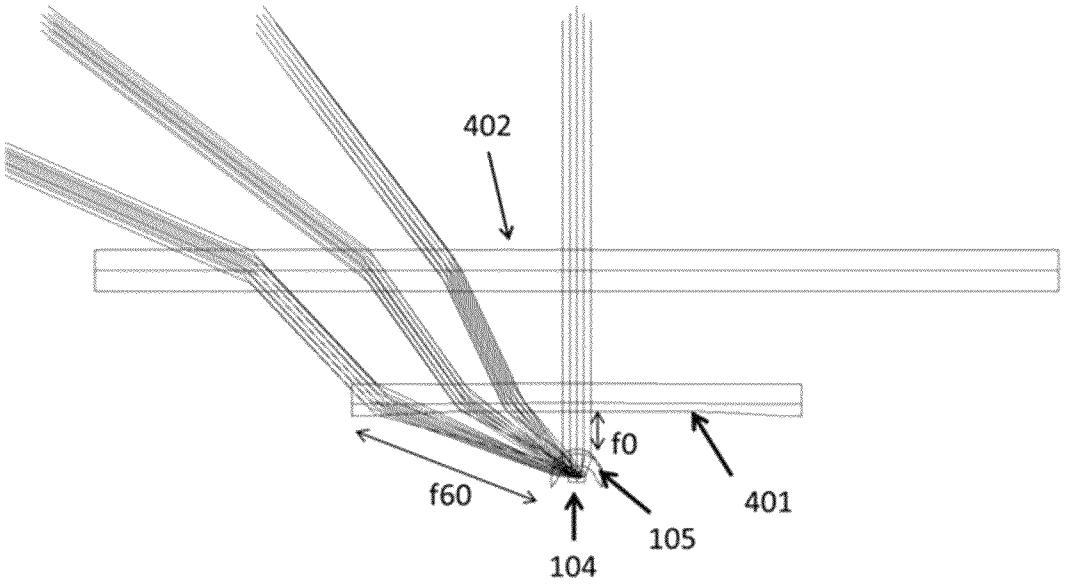

FIG. 38

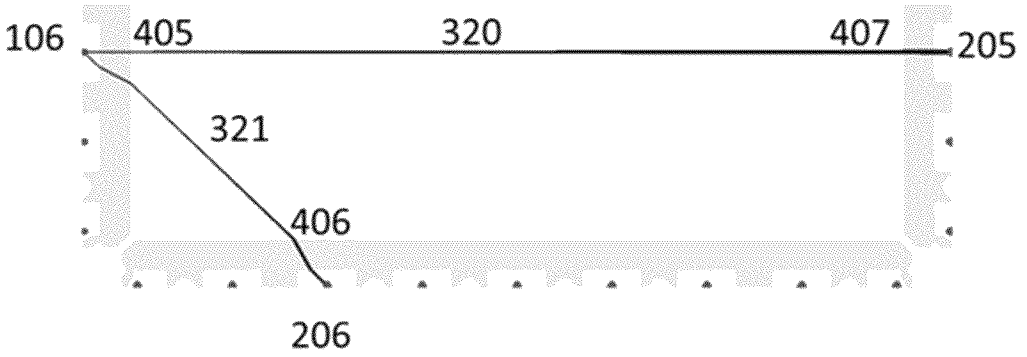

FIG. 39

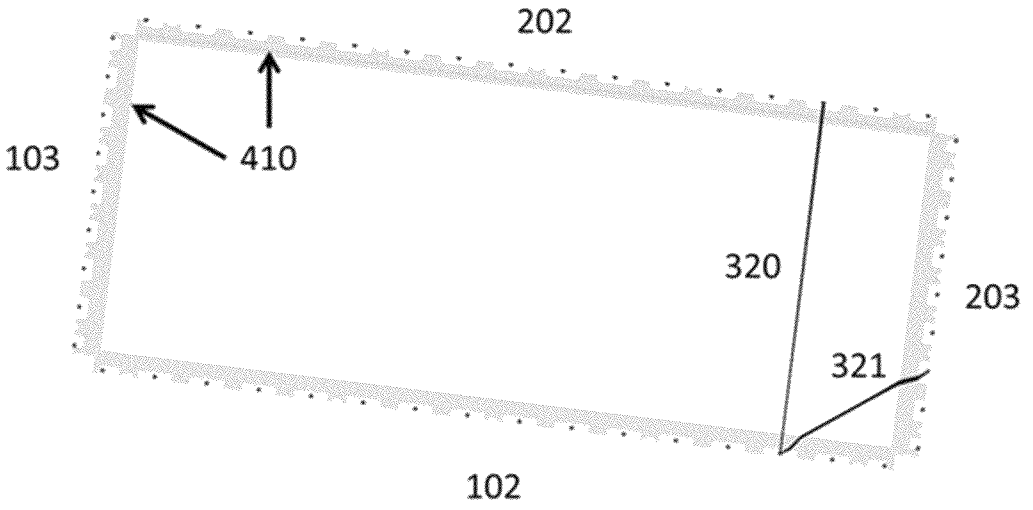

FIG. 40

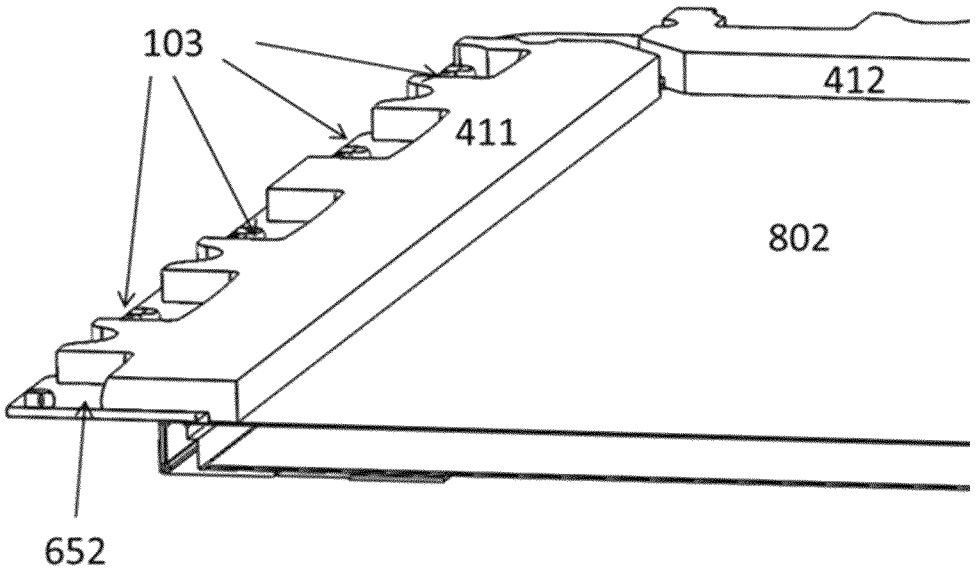

FIG. 41

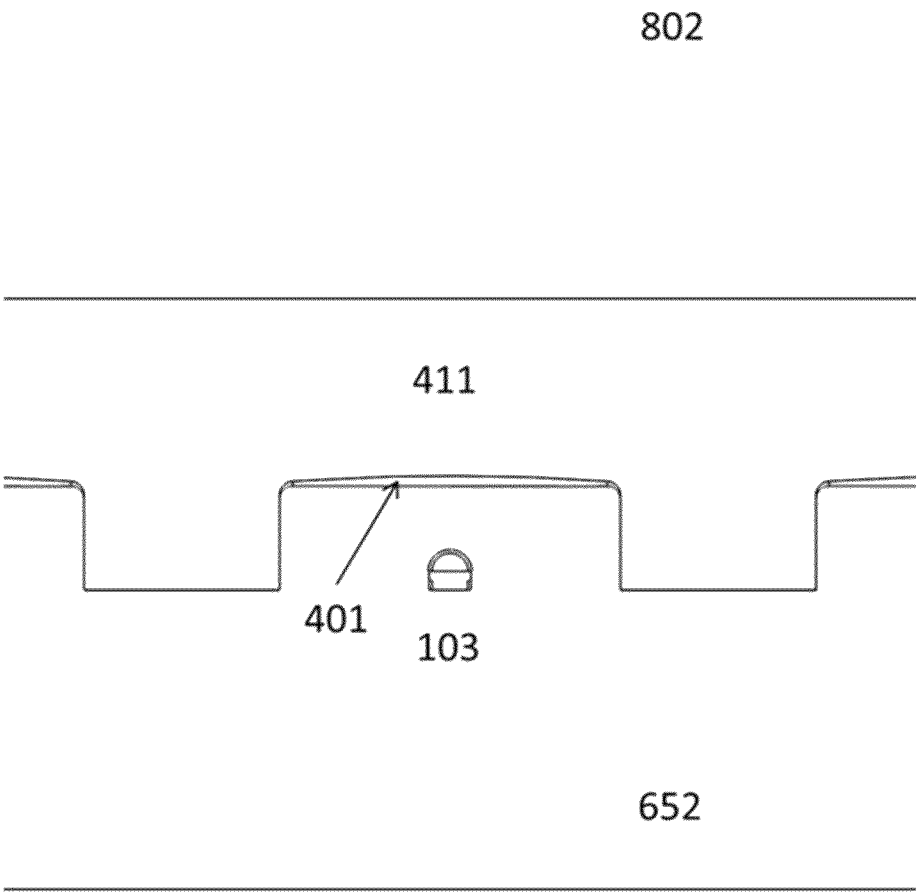

FIG. 42

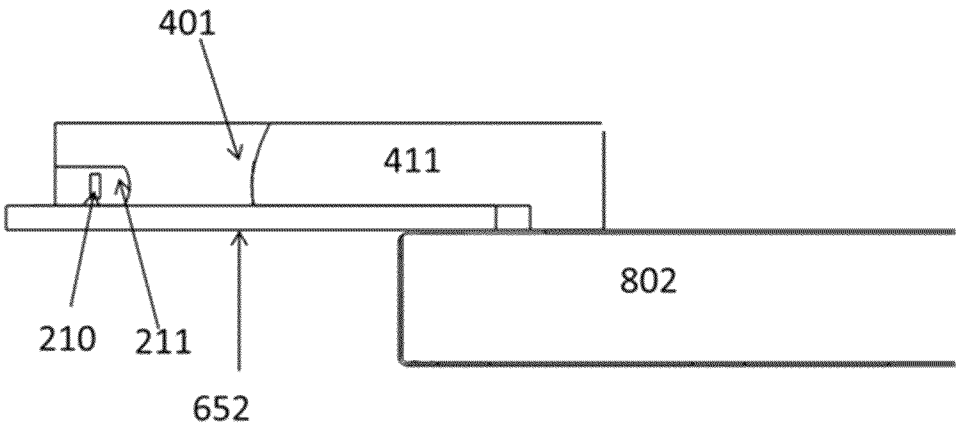

FIG. 43

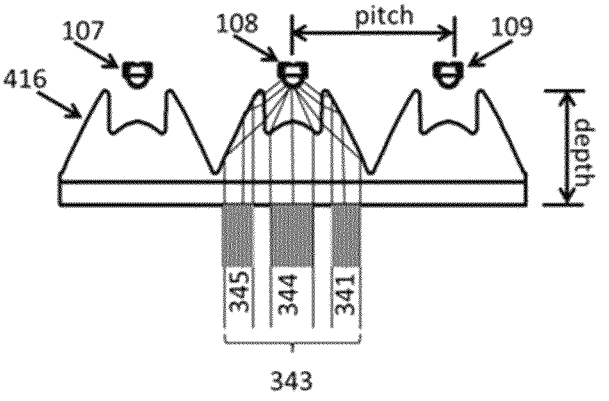

FIG. 44

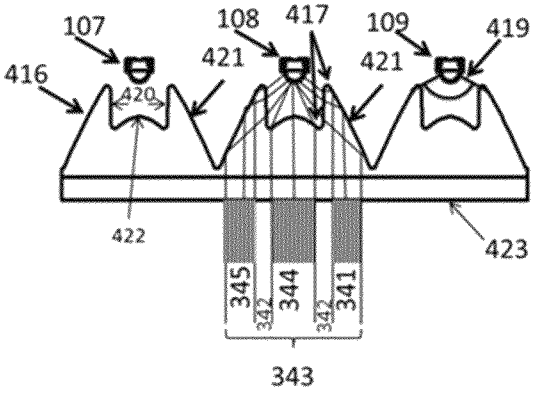
107
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FIG. 45

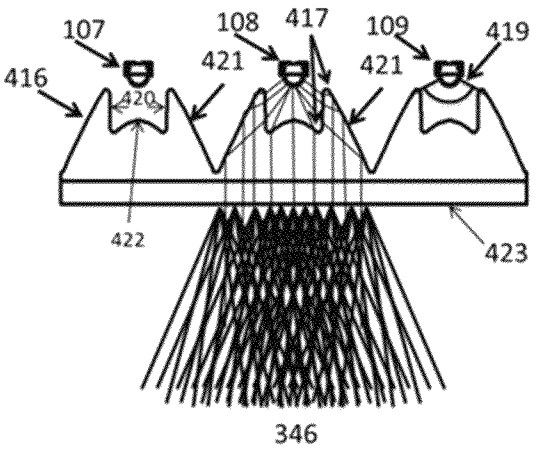

FIG. 46

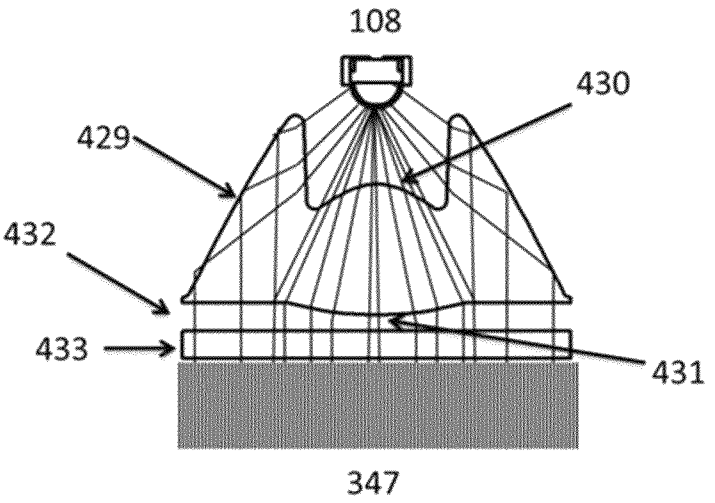

FIG. 47

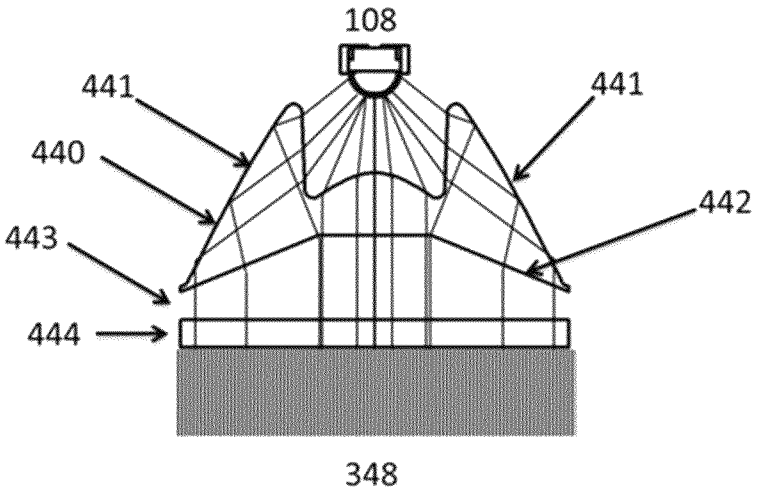

FIG. 48

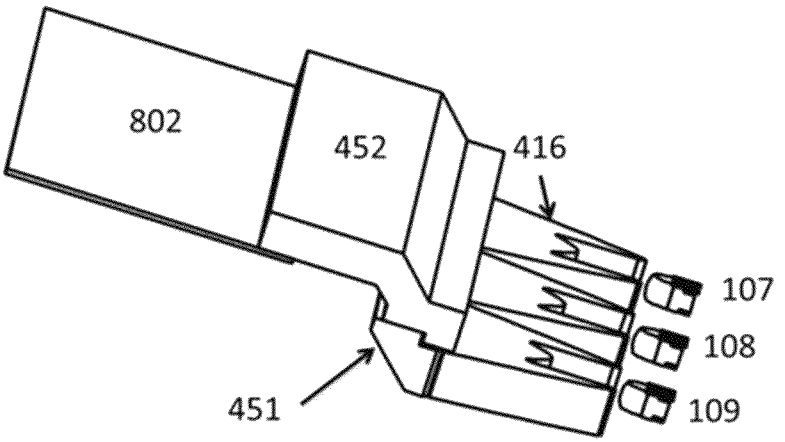

FIG. 49

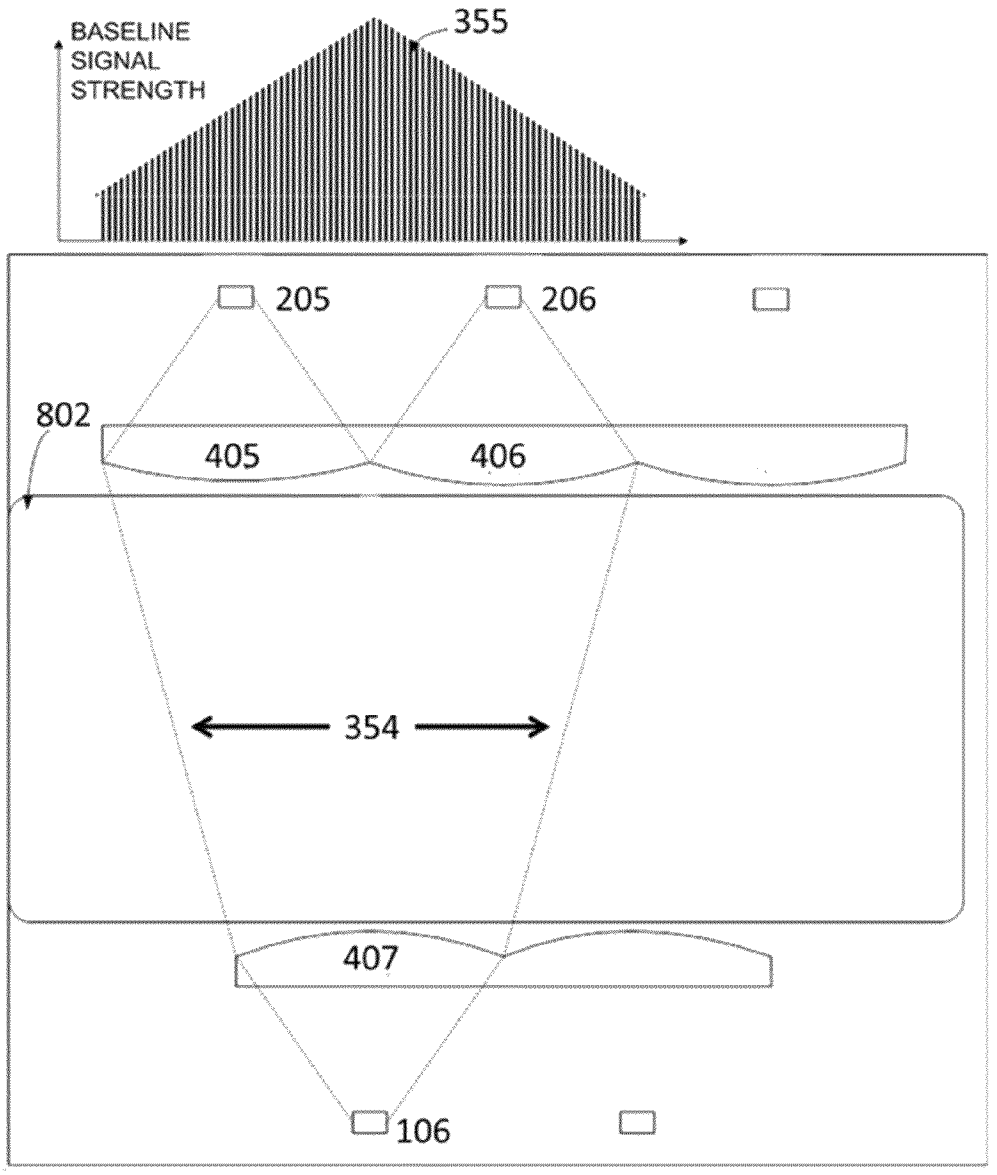

FIG. 50

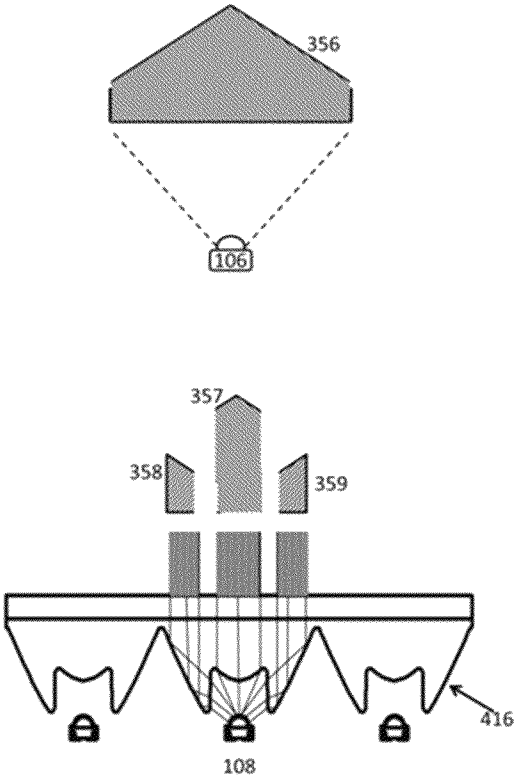

FIG. 51

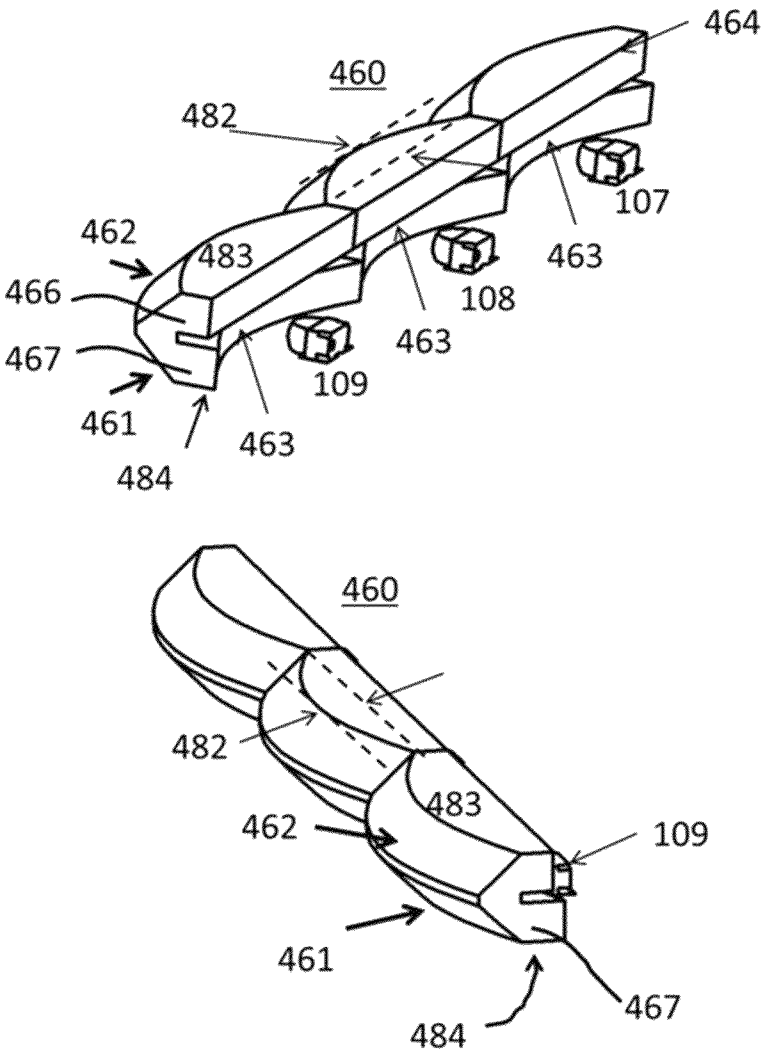
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FIG. 52

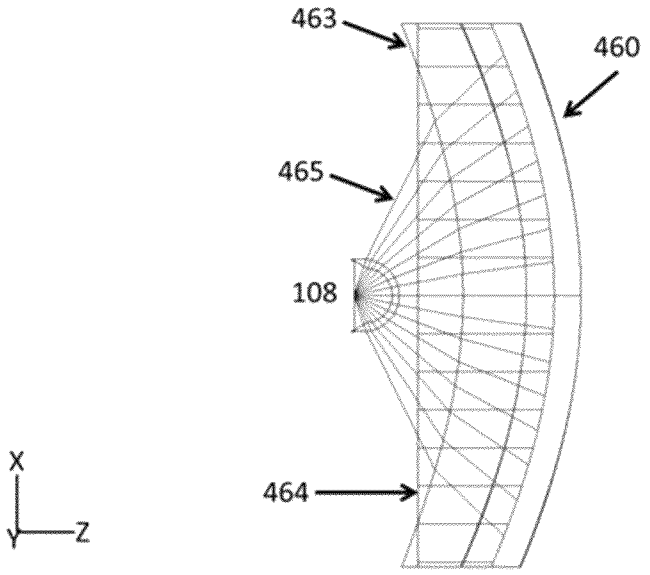


FIG. 53

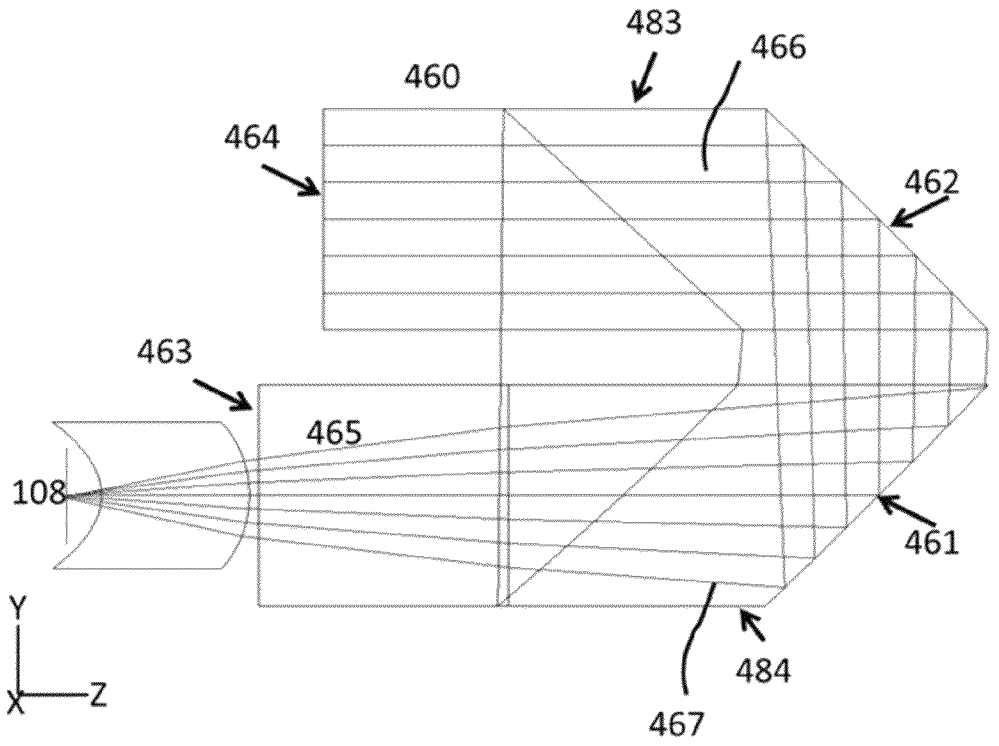


FIG. 54

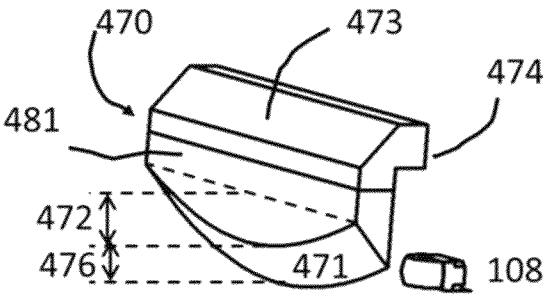


FIG. 55
(PRIOR ART)

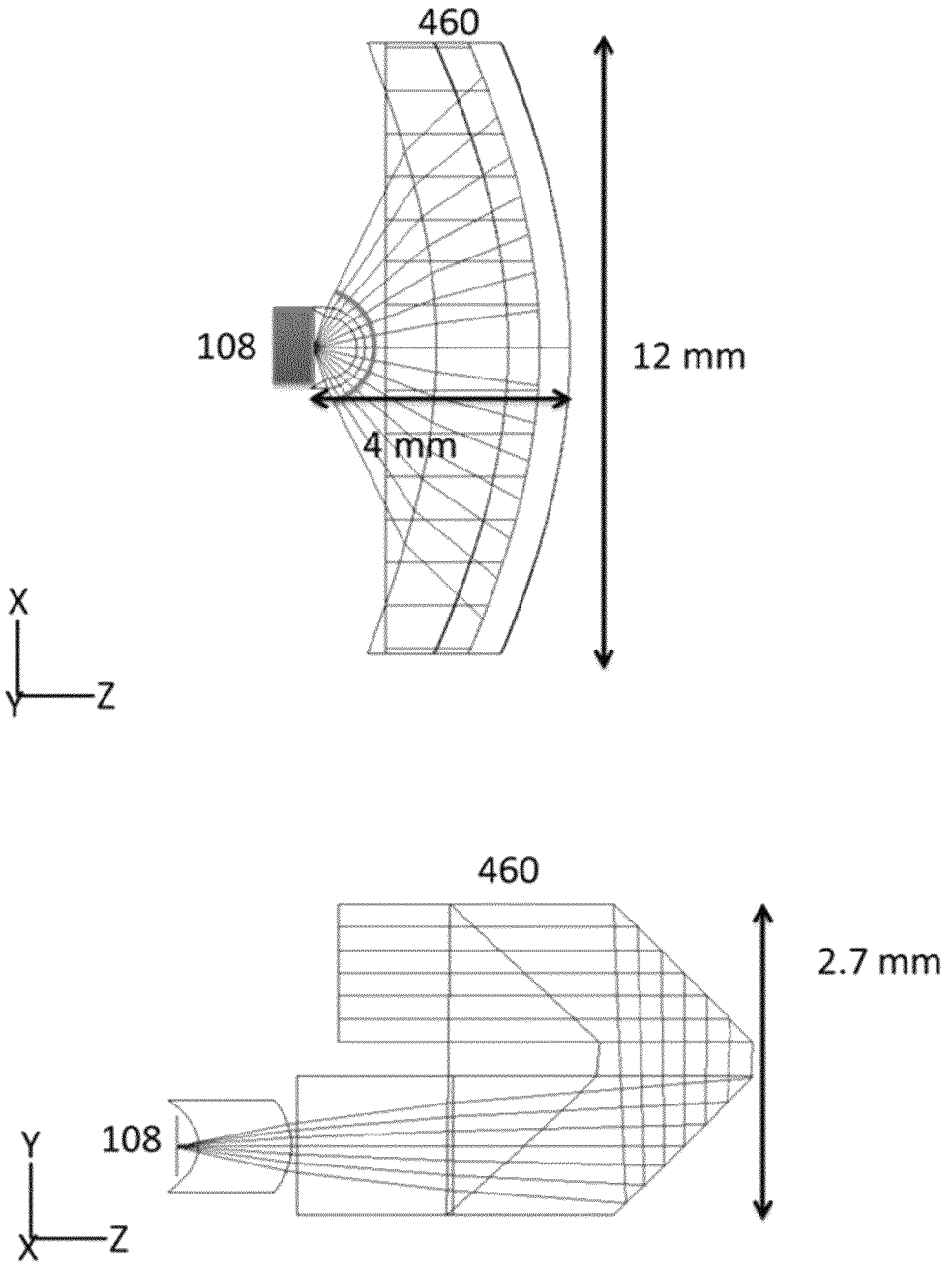


FIG. 56

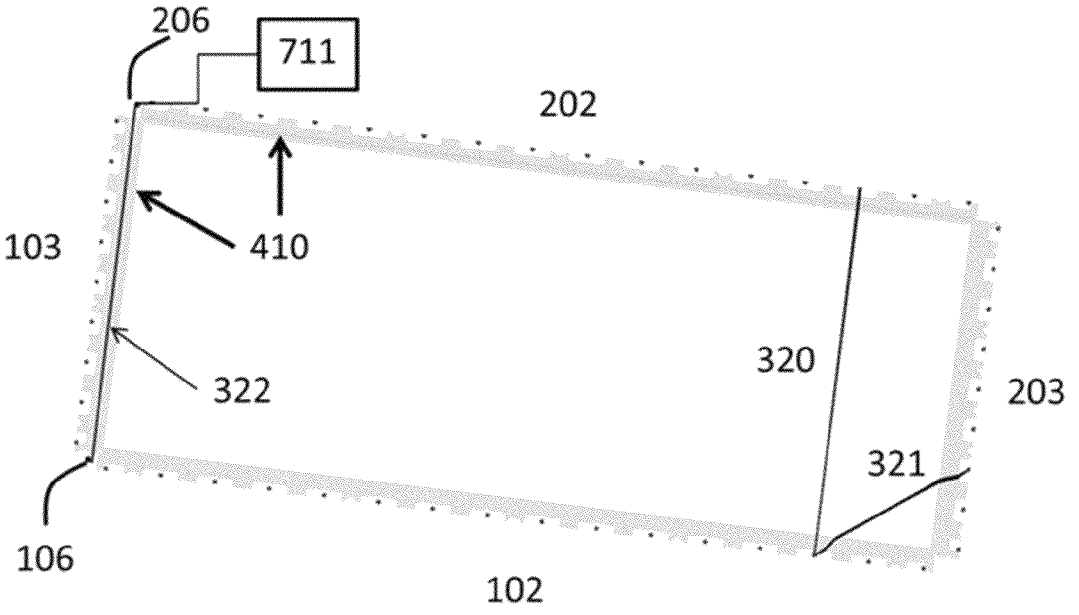


FIG. 57

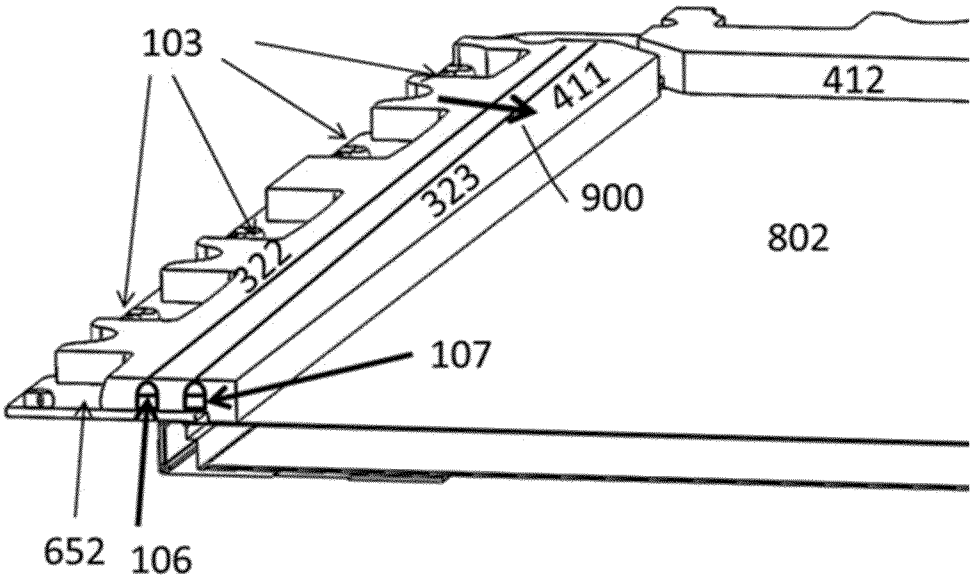


FIG. 58

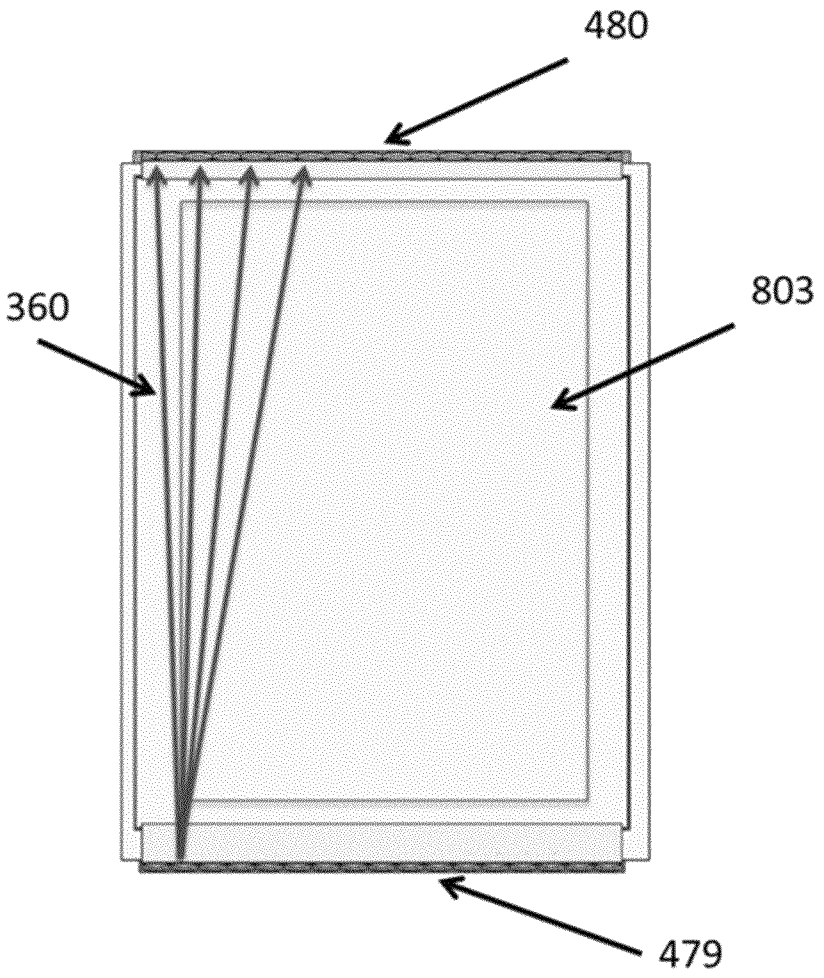


FIG. 59

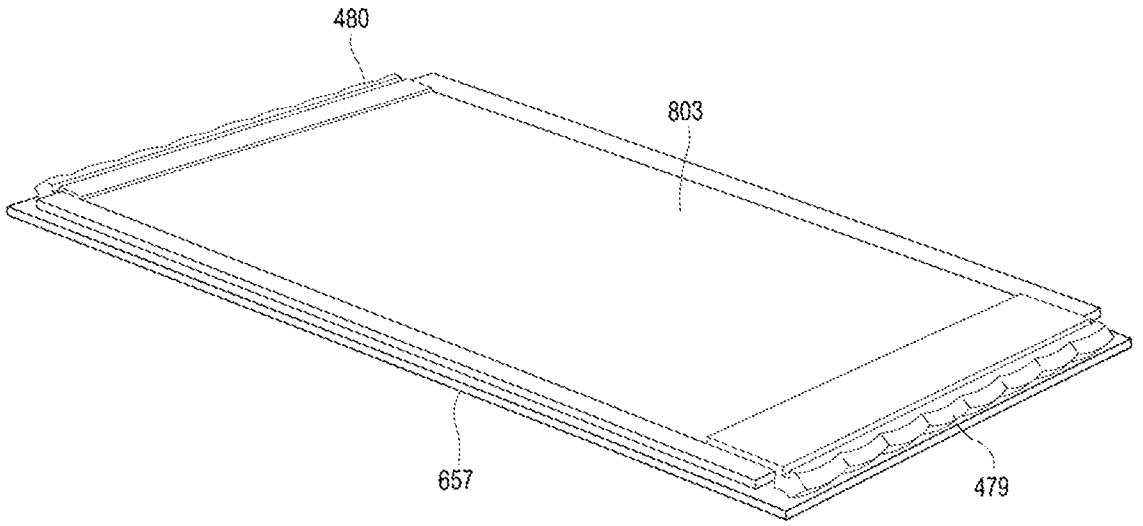


FIG. 60

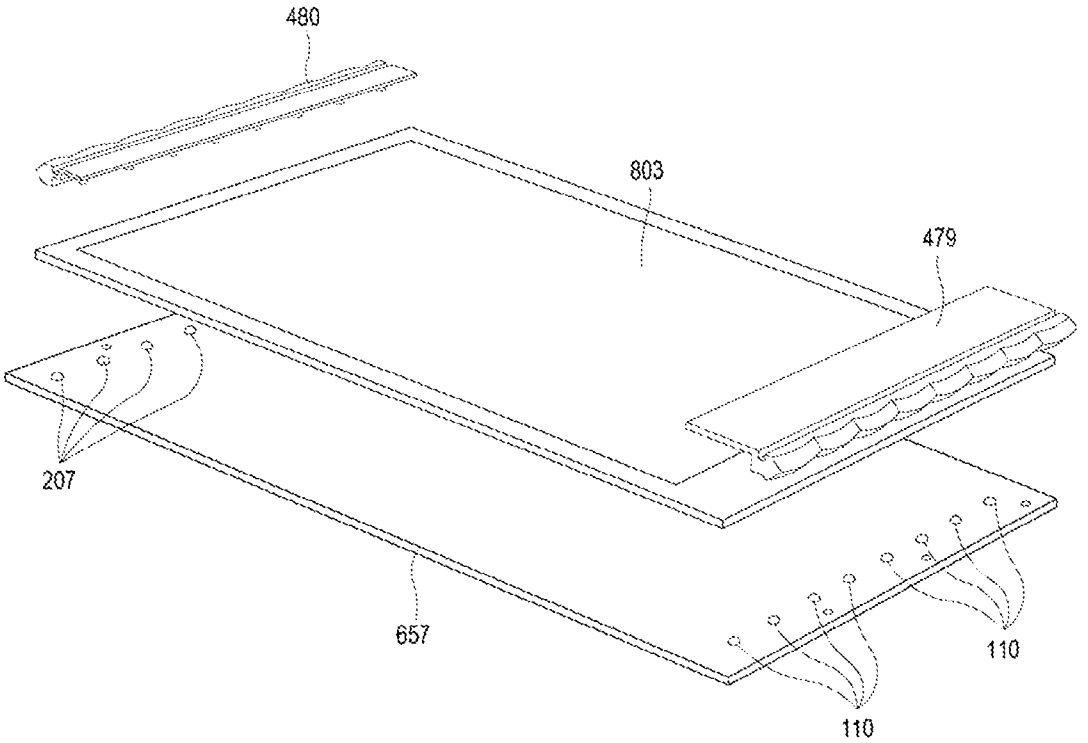


FIG. 61

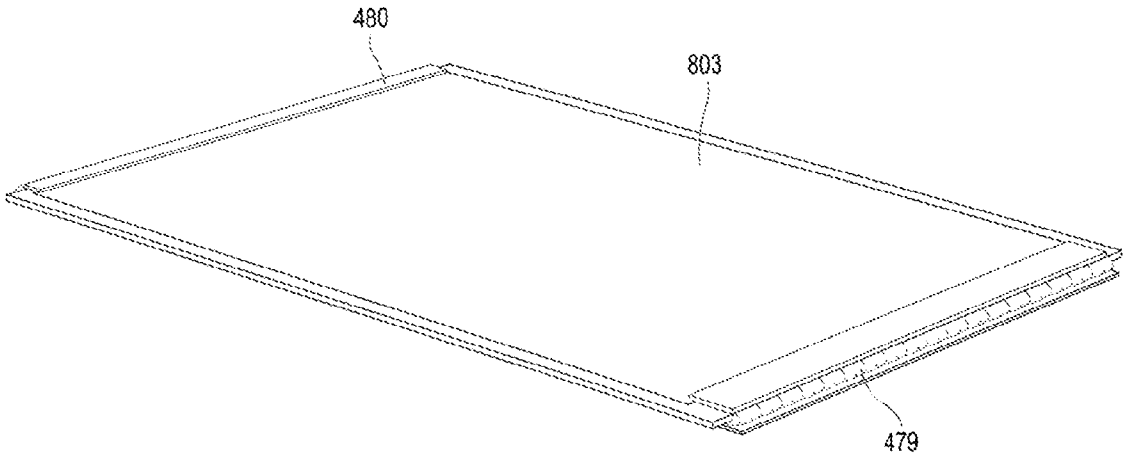


FIG. 62

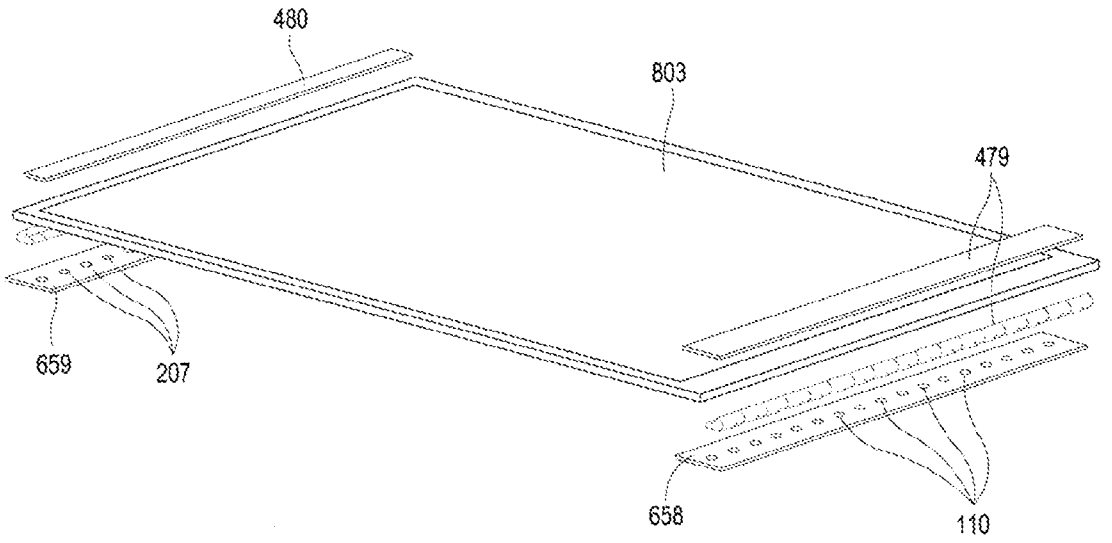


FIG. 63

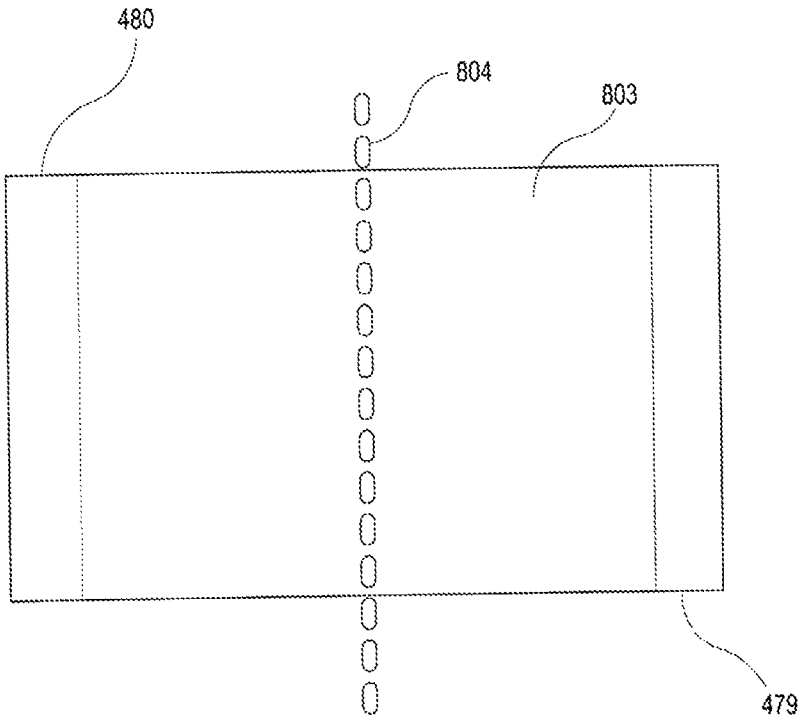


FIG. 64

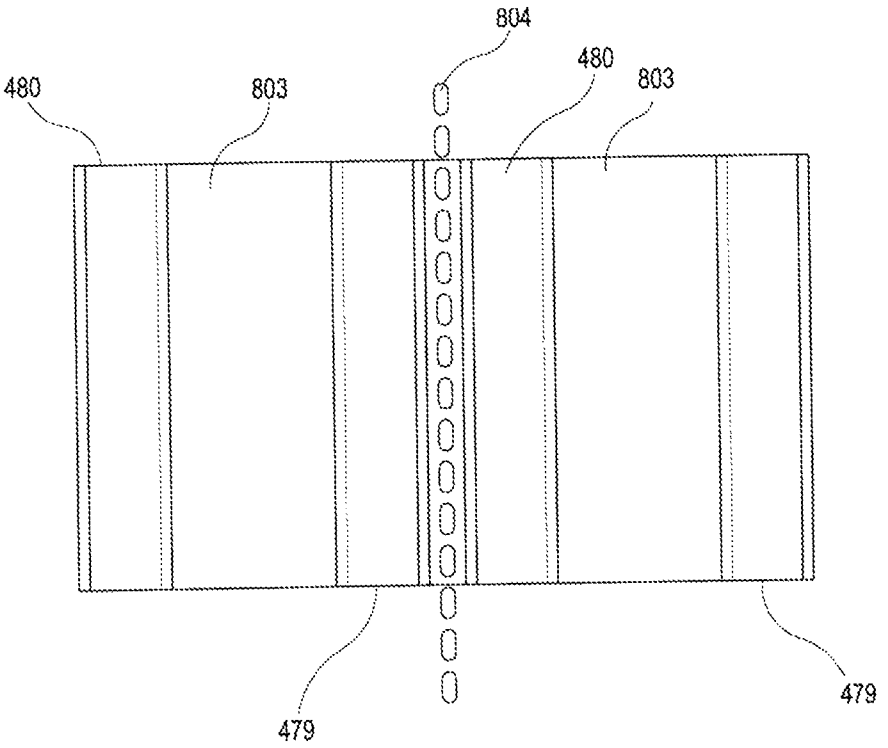


FIG. 65

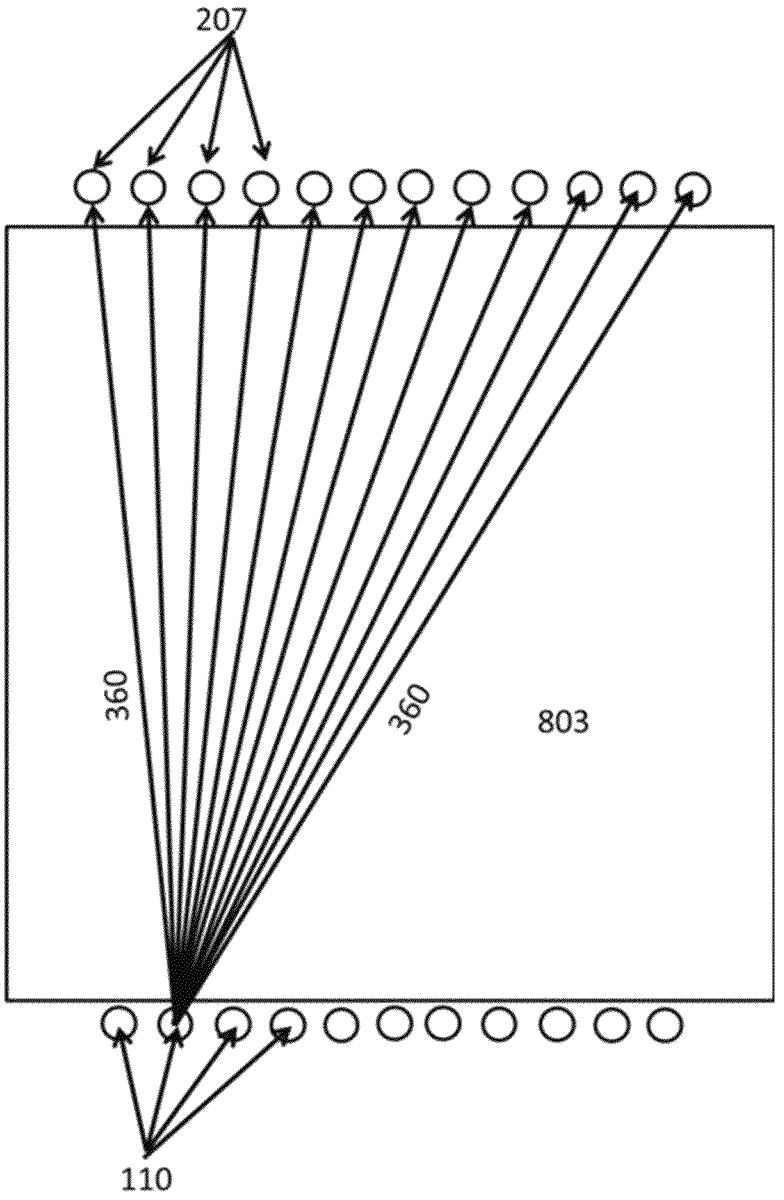


FIG. 66

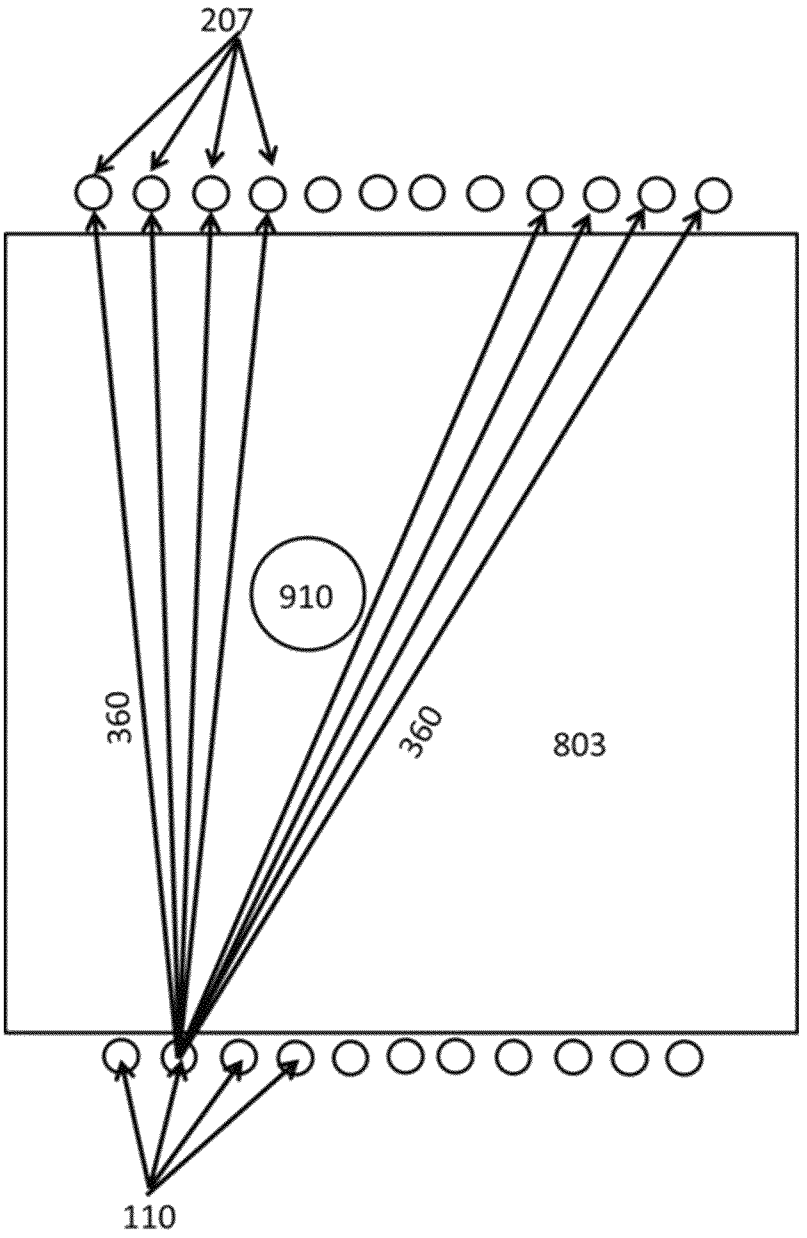


FIG. 67

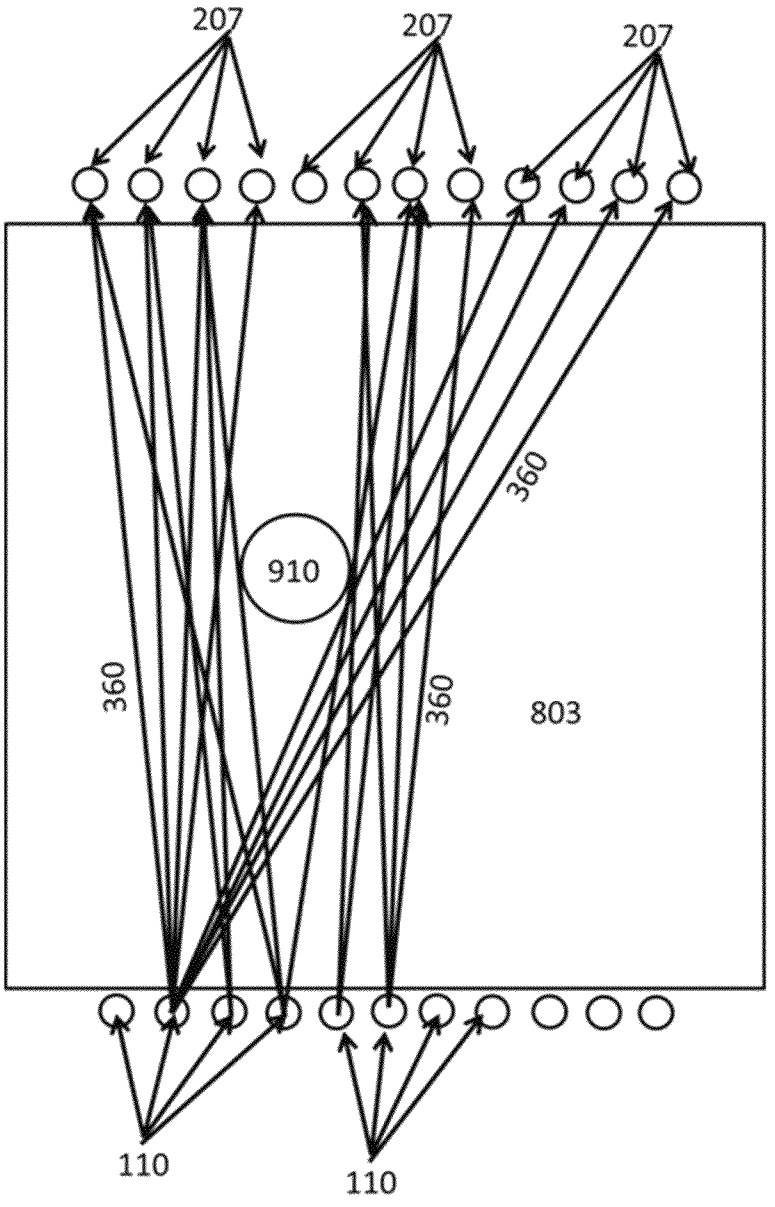


FIG. 68

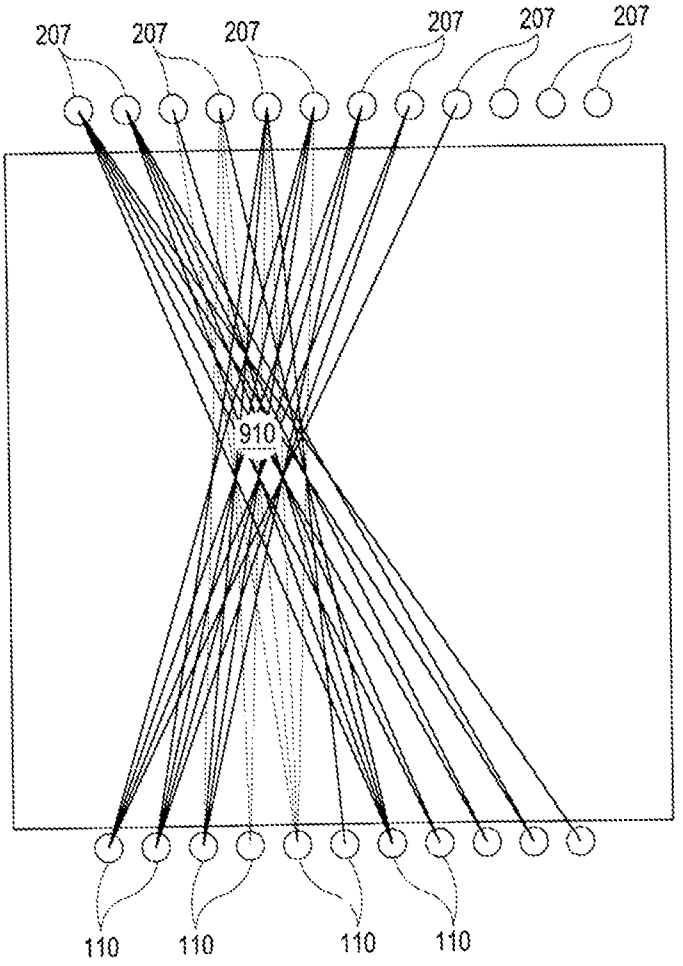
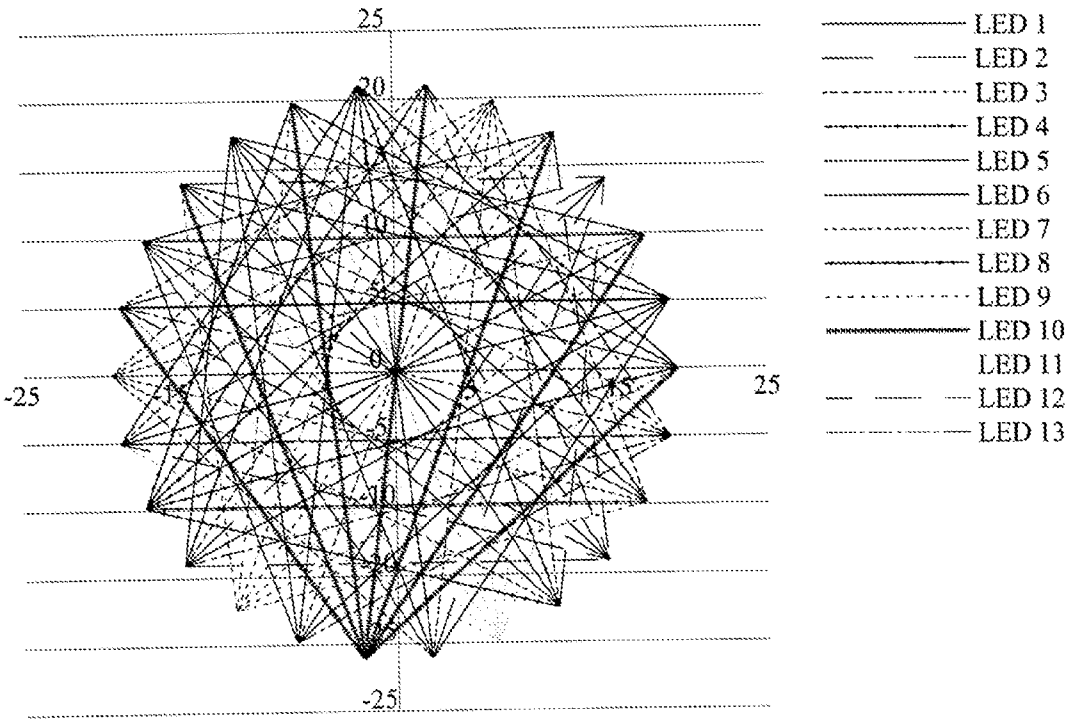


FIG. 69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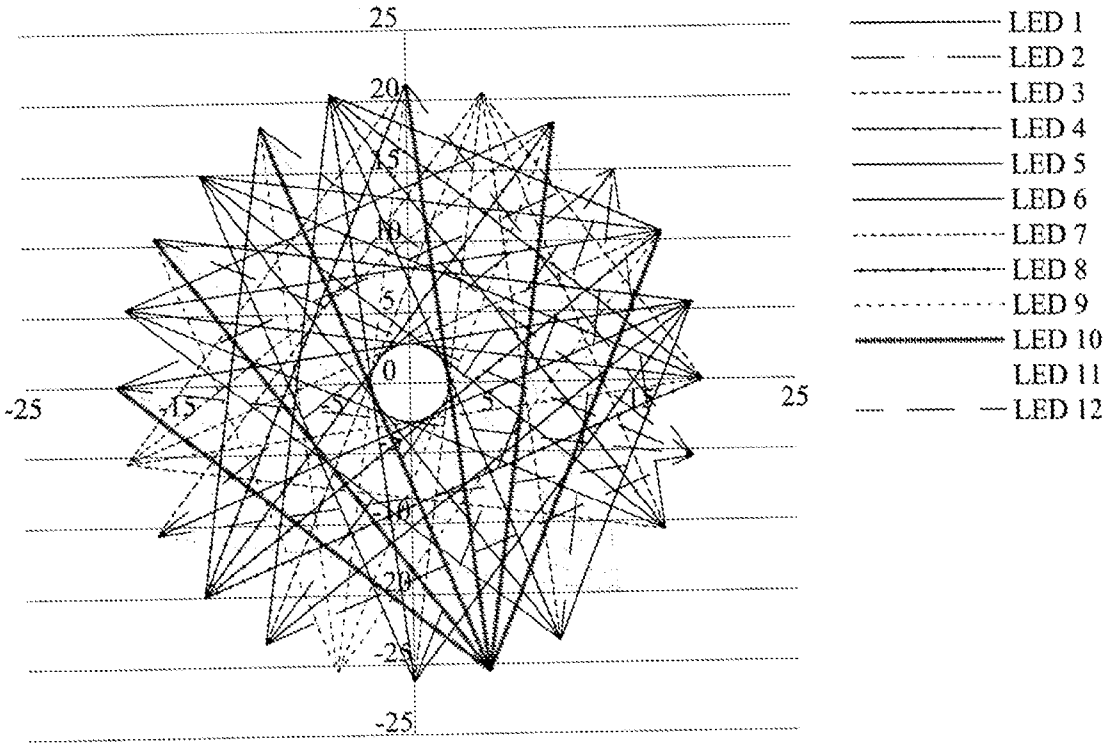
LED 13

FIG. 70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20
15
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-5
-10
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-20
-25
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LED 1
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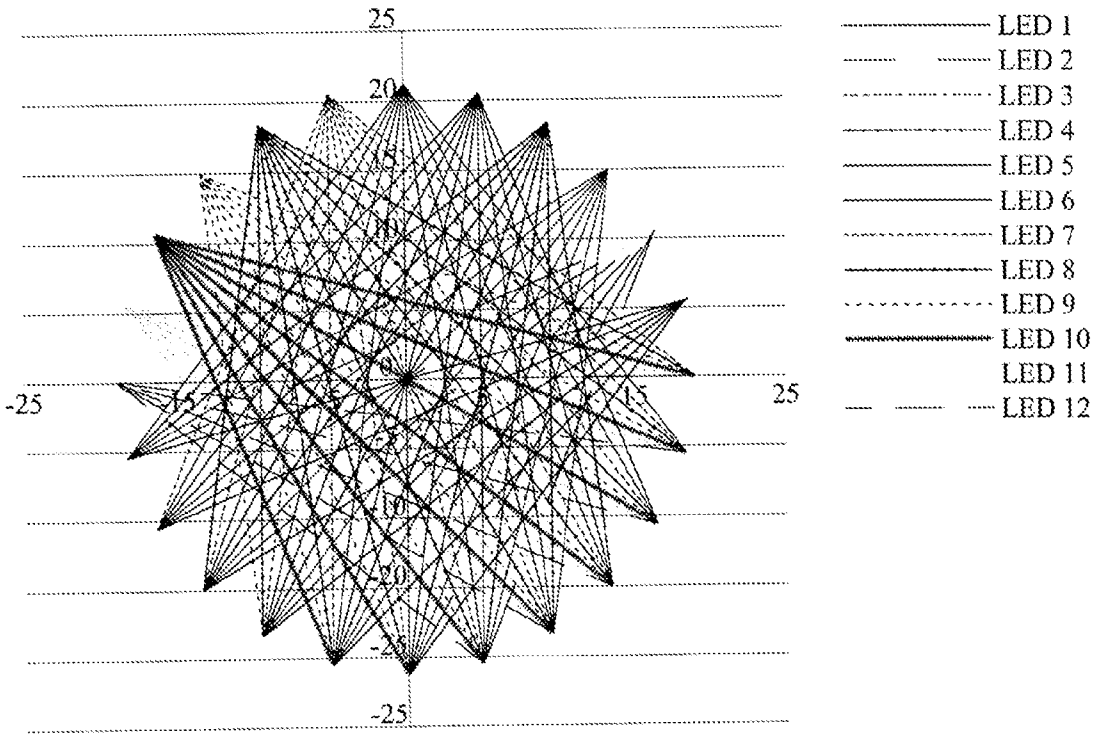
LED 10
LED 11
LED 12

FIG. 71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LED 1
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LED 9
LED 10
LED 11
LED 12

FIG. 72

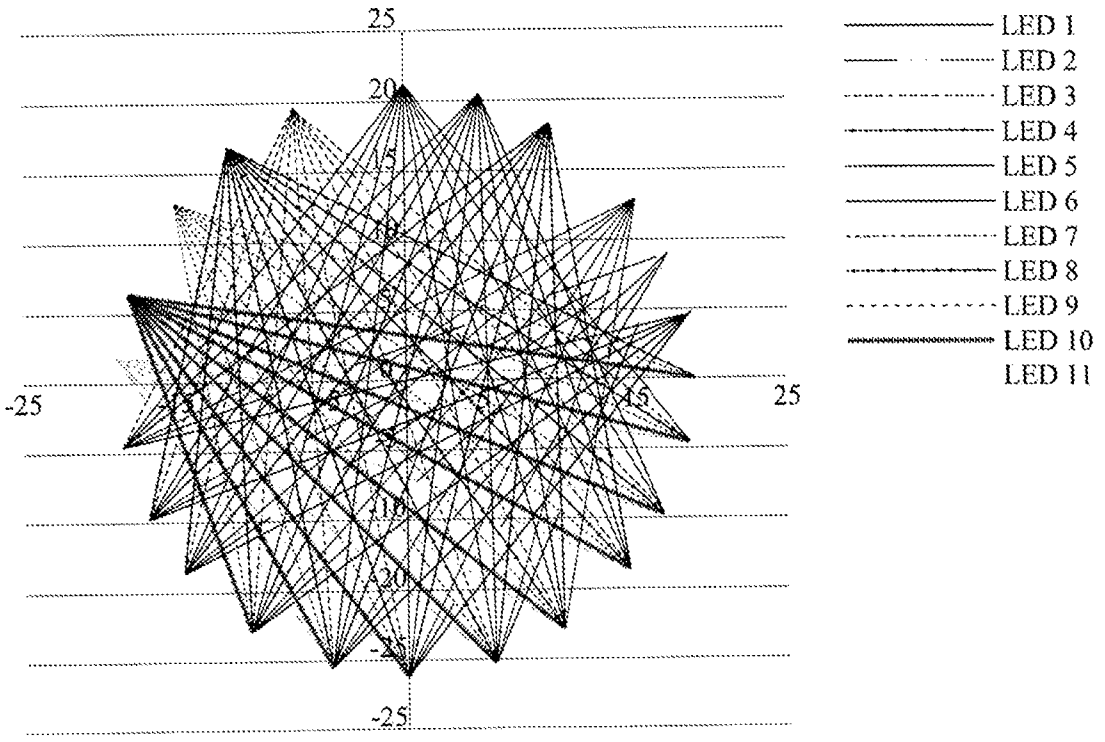
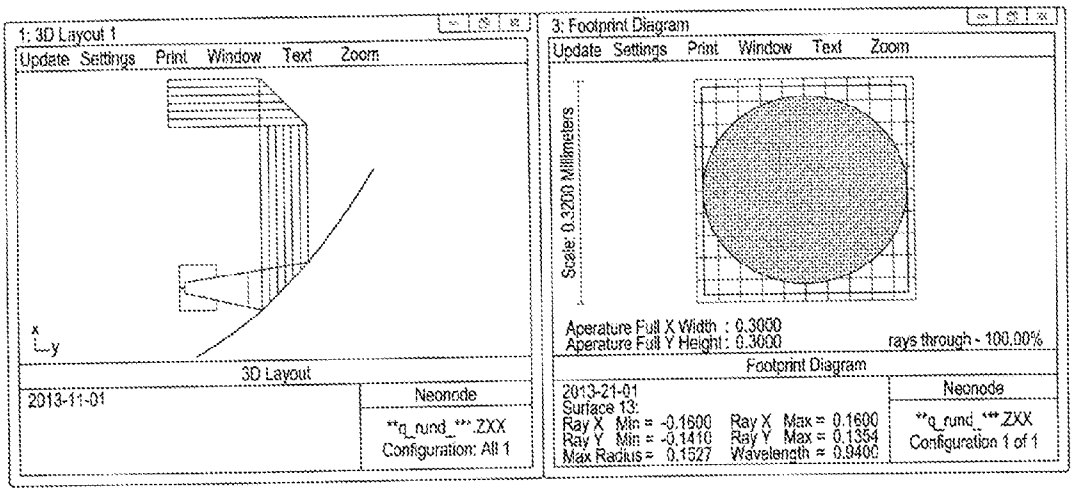

25
20
-25
25
-25
LED 1
LED 2
LED 3
LED 4
LED 5
LED 6
LED 7
LED 8
LED 9
LED 10
LED 11

FIG. 73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Update Settings Print Window Text Zoom
x
y
3D Layout
2013-11-01
Neonode
q_rund_.ZXX
Configuration: All 1
3: Footprint Diagram
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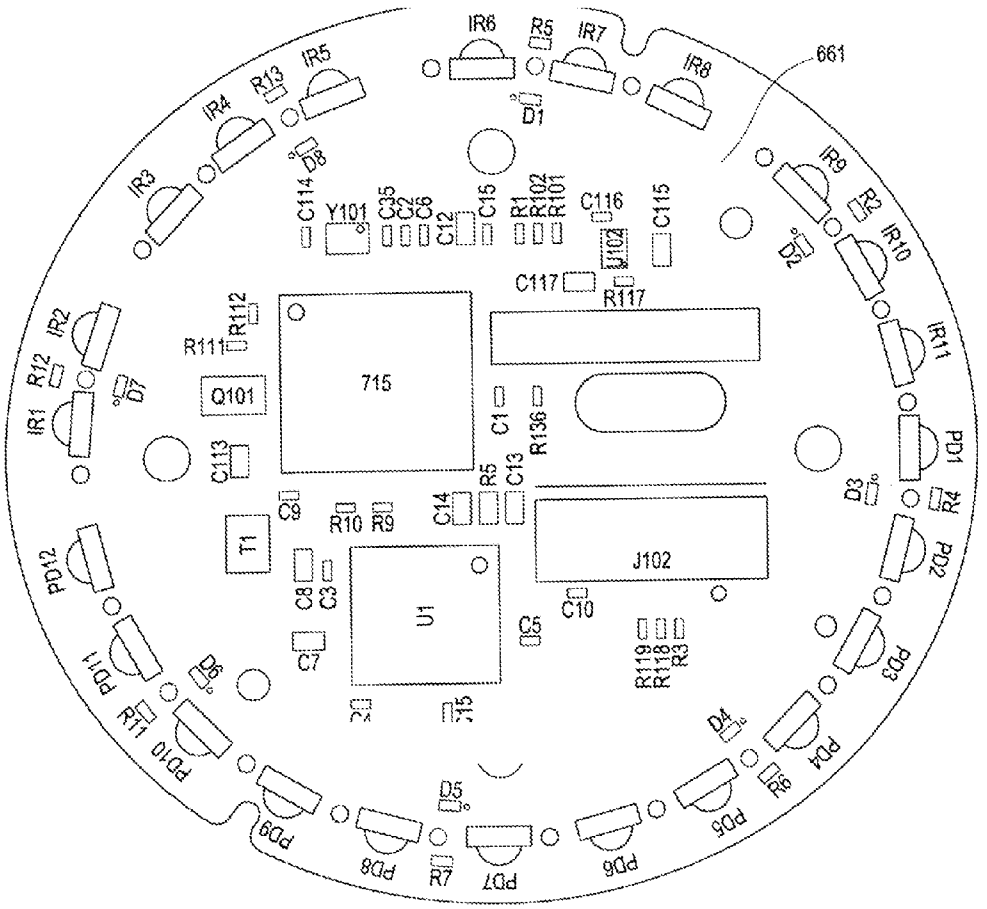
Scale: 0.3200 Millimeters
Aperature Full X Width : 0.3000
Aperature Full Y Height : 0.3000
rays through - 100.00%
Footprint Diagram
2013-21-01
Surface 13:
Ray X Min = -0.1600 Ray X Max = 0.1600
Ray Y Min = -0.1410 Ray Y Max = 0.1354
Max Radius = 0.1527 Wavelength = 0.9400
Neonode
q_rund_.ZXX
Configuration 1 of 1

FIG. 74


661
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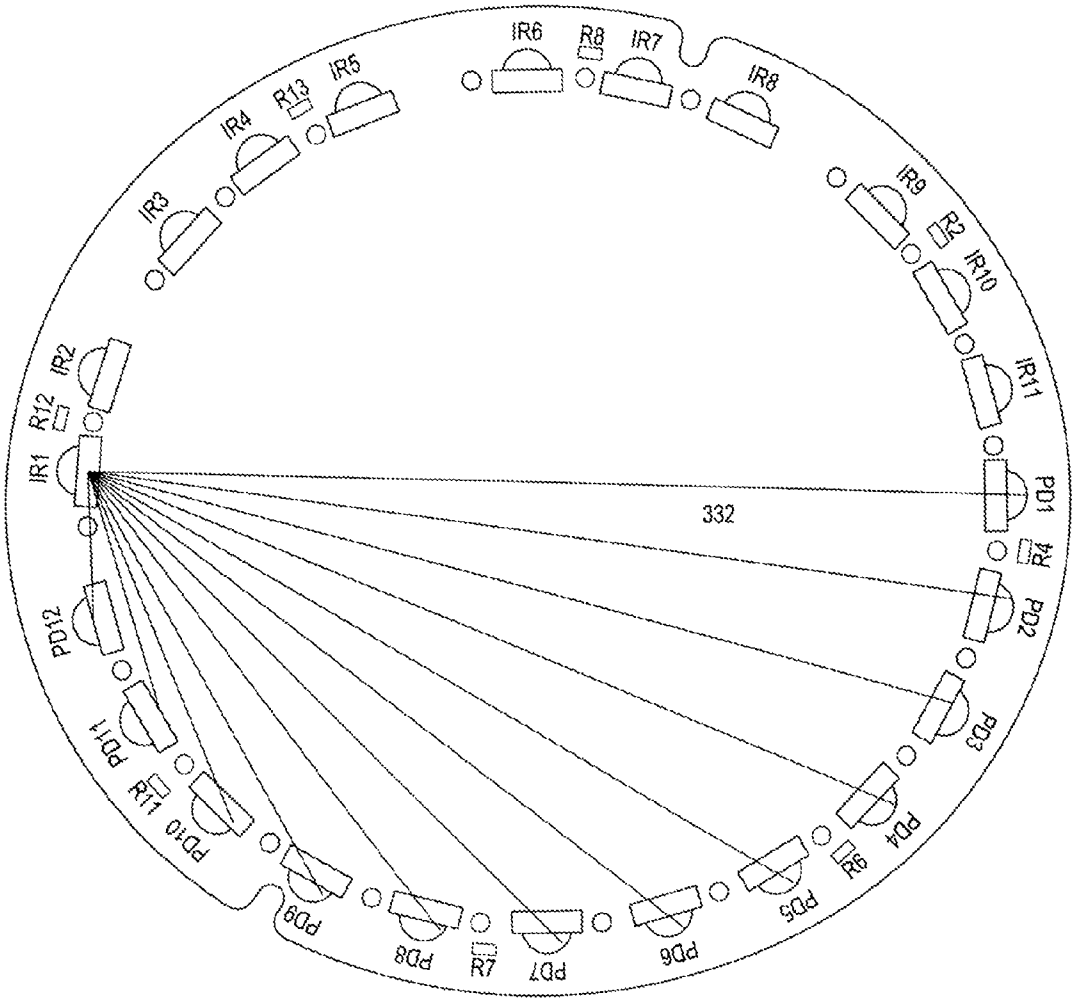
IR2
IR3
IR4
IR5
IR6
IR7
IR8
IR9
IR10
IR11
IR12
R12
R13
R5
R2
R4
D1
D2
D3
D4
D5
D6
D7
D8
PD1
PD2
PD3
PD4
PD5
PD6
PD7
PD8
PD9
PD10
PD11
PD12
R11
R7
R6
C114
Y101
C35
C32
C36
C12
C15
R1
R102
R101
C116
C115
J104
C117
R117
R112
R111
Q101
715
C1
R136
C113
C13
C9
R10
R9
C14
T1
J102
C8
C3
U1
C10
C5
C7
R119
R118
R3

FIG. 75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R8
IR7
IR8
IR5
R13
IR4
IR3
IR9
R3
IR10
IR11
IR2
R12
IR1
332
PD1
R4
PD2
PD3
PD4
R6
PD5
PD6
PD7
R7
PD8
PD9
PD10
R11
PD11
PD12

FIG. 76

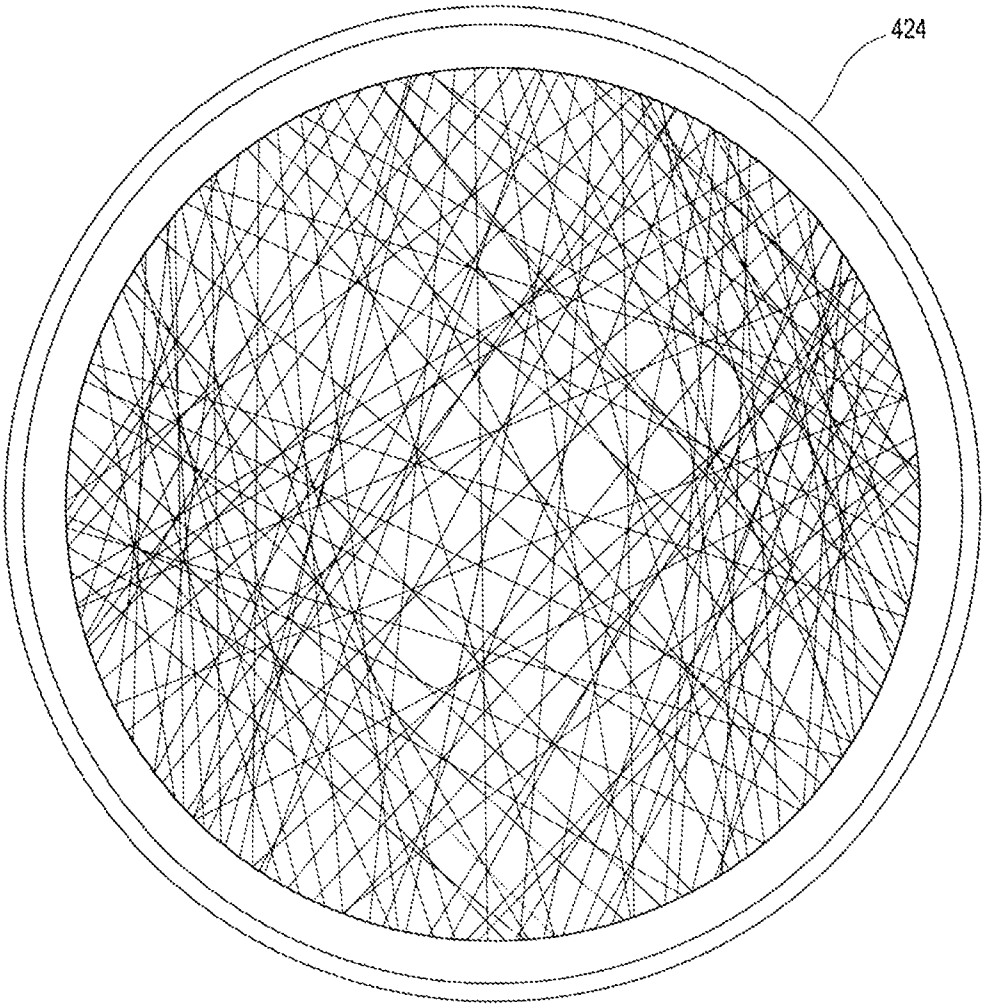

FIG. 77

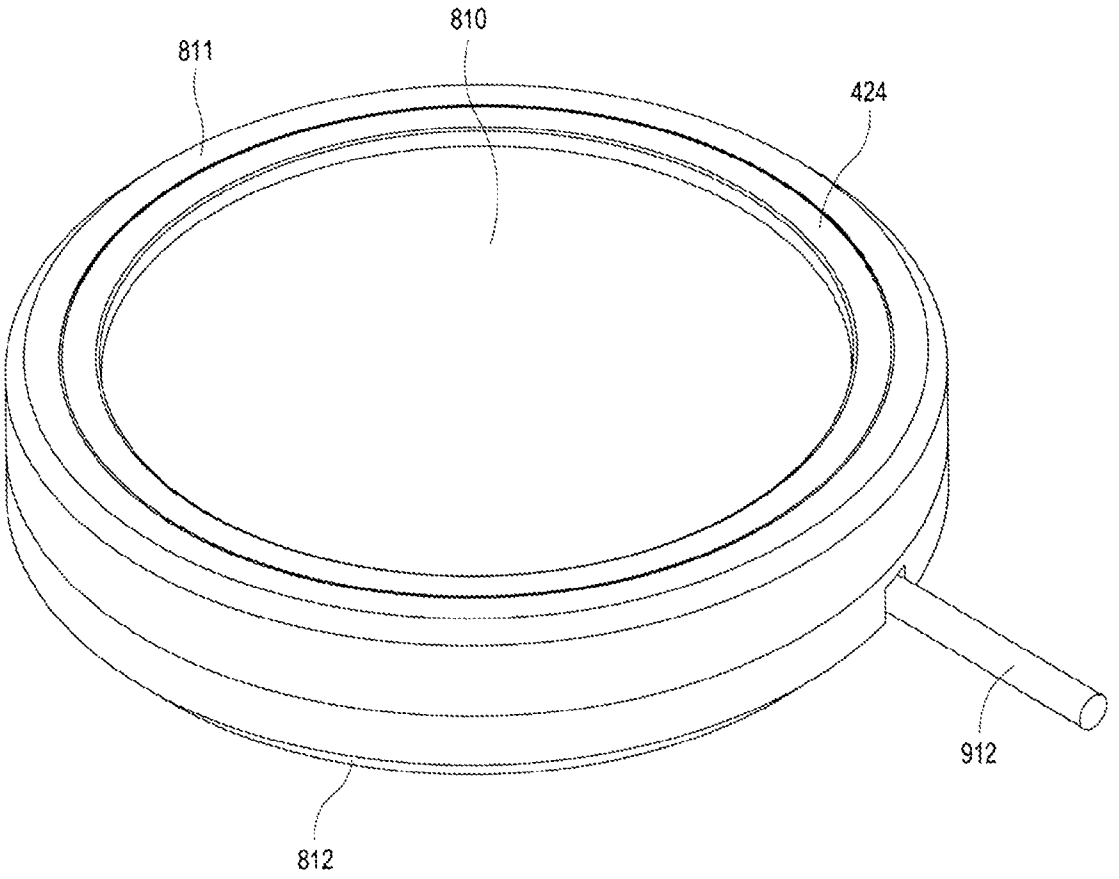

FIG. 78

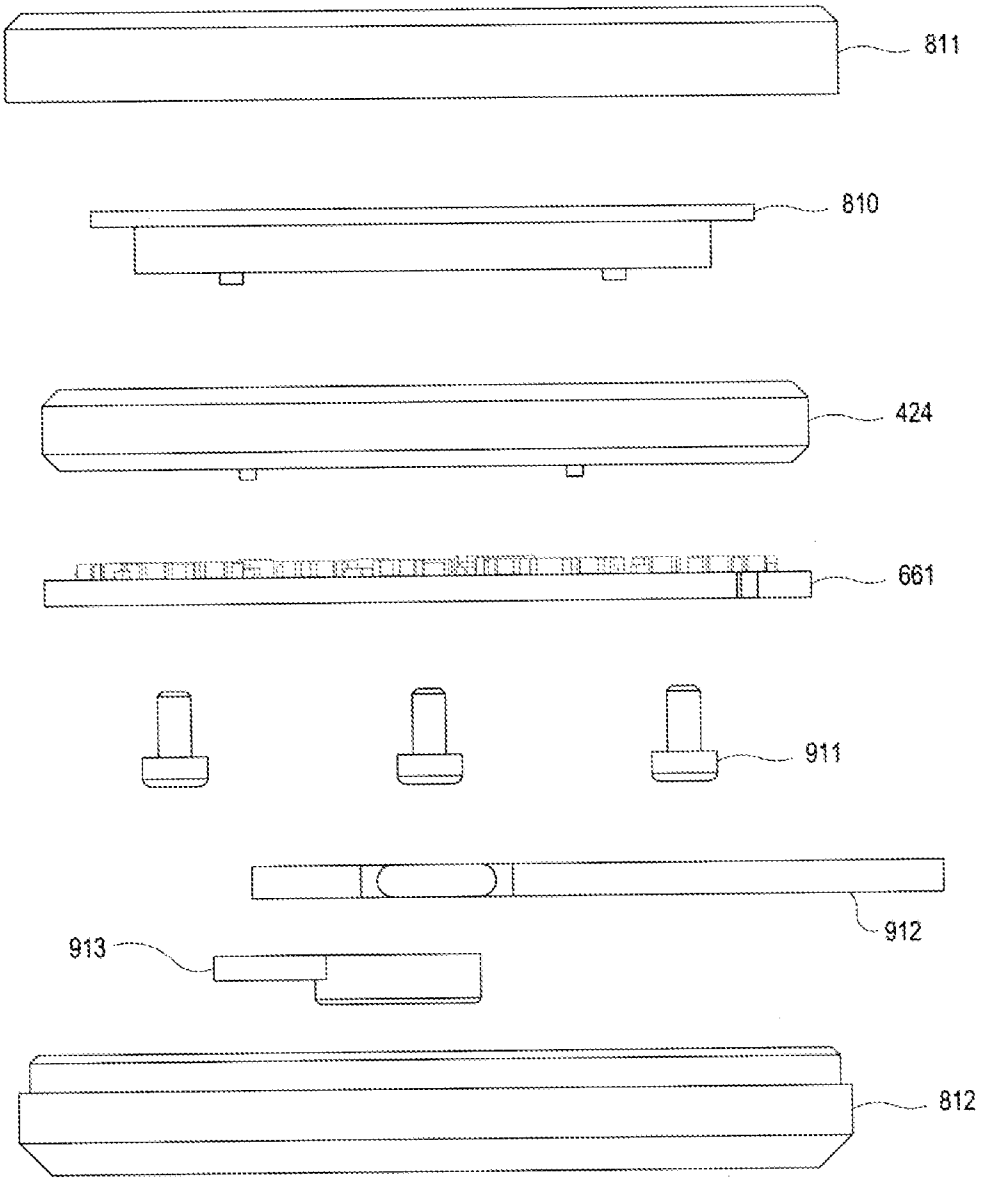

FIG. 79

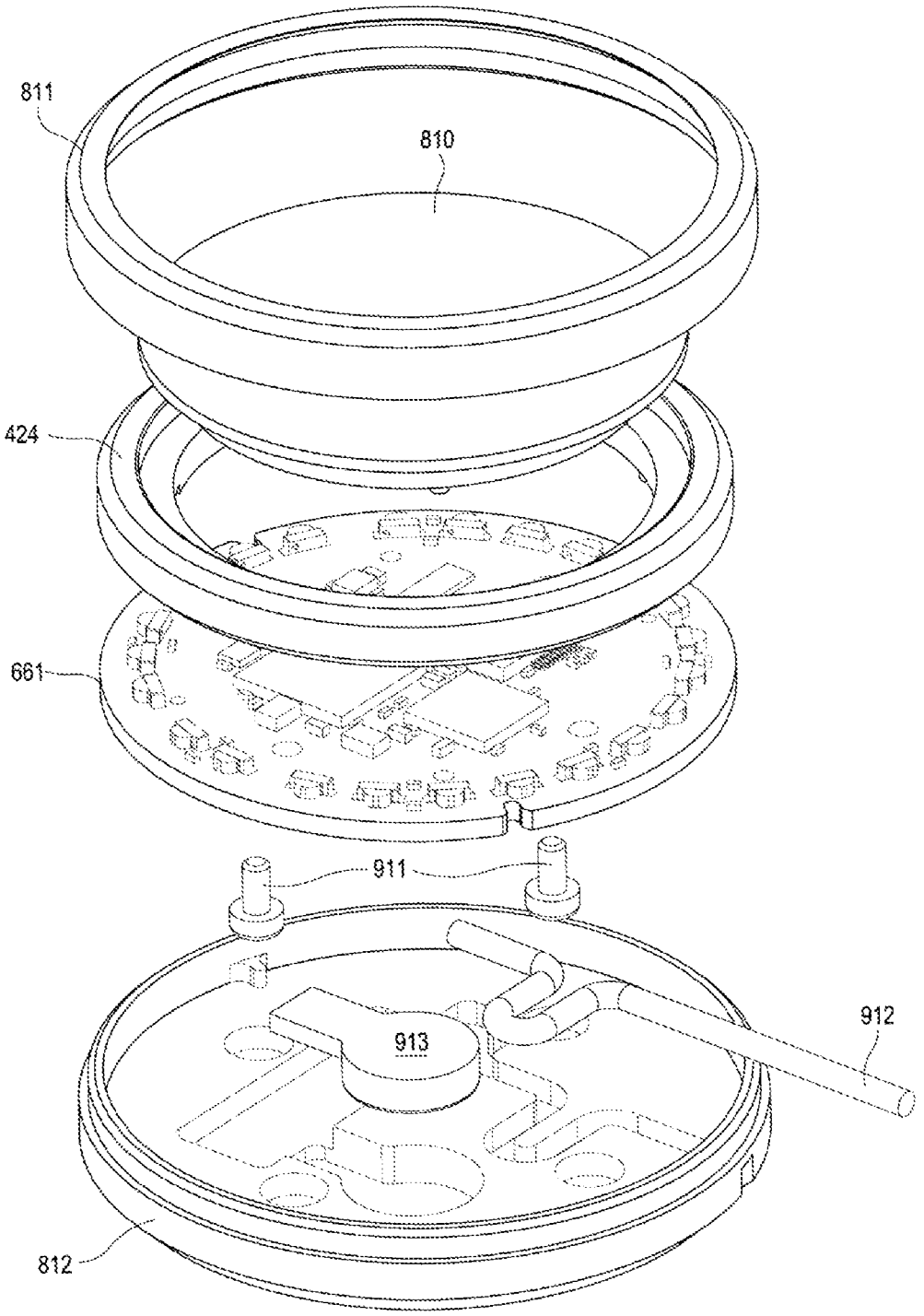

FIG. 80

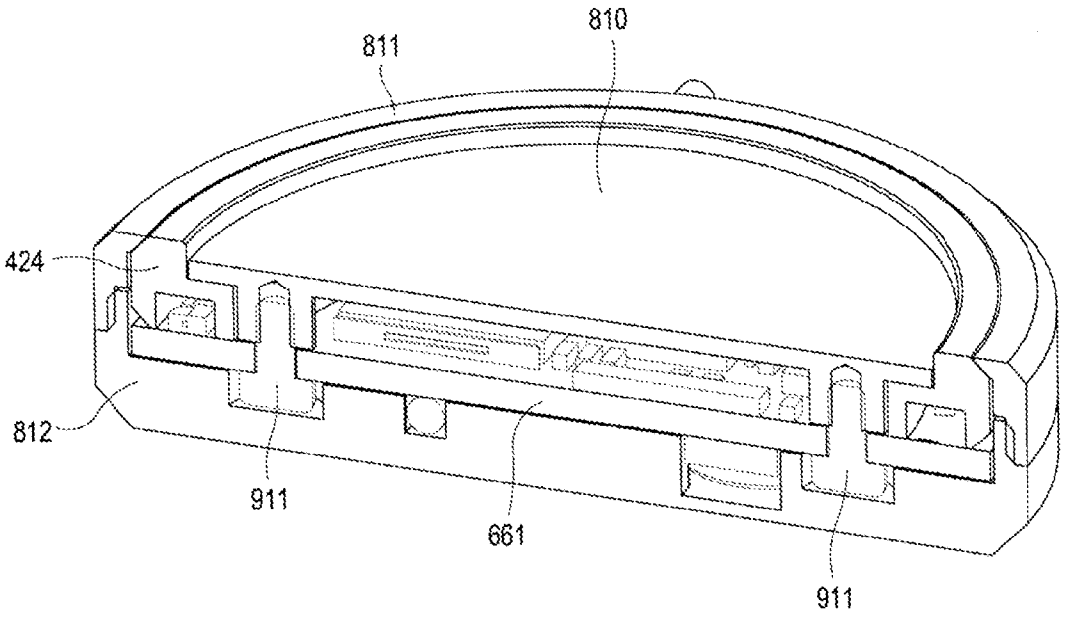

FIG. 81

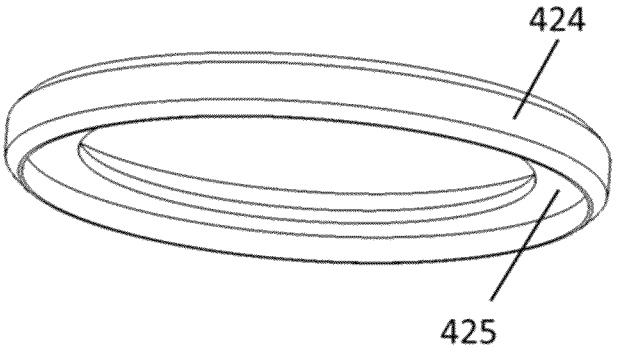

FIG. 82

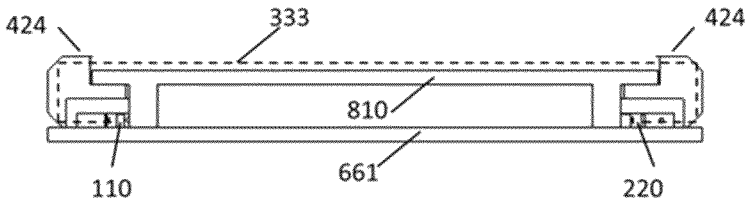

FIG. 83

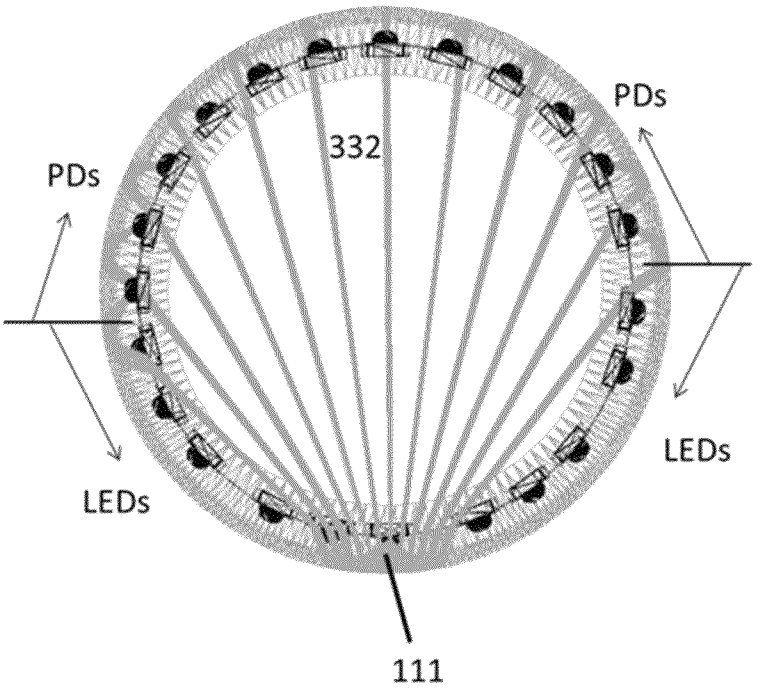

FIG. 84

OPTICAL TOUCH SCREENS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of PCT Patent Application No. PCT/US14/40579, entitled OPTICAL TOUCH SCREENS, and filed on Jun. 3, 2014 by inventors Robert Pettersson, Per Rosengren, Erik Rosengren, Stefan Holmgren, Lars Sparf, Richard Berglind, Thomas Eriksson, Karl Erik Patrik Nordström, Gunnar Martin Fröjdh, Xiatao Wang and Remo Behdasht.

This application is a continuation-in-part of U.S. patent application Ser. No. 13/052,511, entitled LIGHT-BASED TOUCH SCREEN WITH SHIFT-ALIGNED EMITTER AND RECEIVER LENSES, and filed on Mar. 21, 2011 by inventors Magnus Goertz, Thomas Eriksson, Joseph Shain, Anders Jansson, Niklas Kvist, Robert Pettersson, Lars Sparf and John Karlsson.

PCT Patent Application No. PCT/US14/40579 claims priority benefit from:

- U.S. Provisional Patent Application No. 61/830,671, entitled MULTI-TOUCH OPTICAL TOUCH SCREENS WITHOUT GHOST POINTS, and filed on Jun. 4, 2013 by inventors Erik Rosengren, Robert Pettersson, Lars Sparf and Thomas Eriksson;
- U.S. Provisional Patent Application No. 61/833,161, entitled CIRCULAR MULTI-TOUCH OPTICAL TOUCH SCREENS, and filed on Jun. 10, 2013 by inventors Richard Berglind, Erik Rosengren, Robert Pettersson, Lars Sparf, Thomas Eriksson, Gunnar Martin Fröjdh and Xiatao Wang;
- U.S. Provisional Patent Application No. 61/919,759, entitled OPTICAL TOUCH SCREENS WITH TOUCH-SENSITIVE BORDERS, and filed on Dec. 22, 2013 by inventors Remo Behdasht, Erik Rosengren, Robert Pettersson, Lars Sparf, Thomas Eriksson;
- U.S. Provisional Patent Application No. 61/911,915, entitled CIRCULAR MULTI-TOUCH OPTICAL TOUCH SCREENS, and filed on Dec. 4, 2013 by inventors Richard Berglind, Erik Rosengren, Robert Pettersson, Lars Sparf, Thomas Eriksson, Gunnar Martin Fröjdh and Xiatao Wang;
- U.S. Provisional Patent Application No. 61/923,775, entitled MULTI-TOUCH OPTICAL TOUCH SCREENS WITHOUT GHOST POINTS, and filed on Jan. 6, 2014 by inventors Per Rosengren, Stefan Holmgren, Erik Rosengren, Robert Pettersson, Lars Sparf and Thomas Eriksson; and
- U.S. Provisional Patent Application No. 61/950,868, entitled OPTICAL TOUCH SCREENS, and filed on Mar. 11, 2014 by inventors Karl Erik Patrik Nordström, Per Rosengren, Stefan Holmgren, Erik Rosengren, Robert Pettersson, Lars Sparf and Thomas Eriksson.

U.S. patent application Ser. No. 13/052,511 claims priority benefit from:

- U.S. Provisional Patent Application No. 61/379,012, entitled OPTICAL TOUCH SCREEN SYSTEMS USING REFLECTED LIGHT, and filed on Sep. 1, 2010 by inventors Magnus Goertz, Thomas Eriksson, Joseph Shain, Anders Jansson, Niklas Kvist and Robert Pettersson;
- U.S. Provisional Patent Application No. 61/380,600, entitled OPTICAL TOUCH SCREEN SYSTEMS USING REFLECTED LIGHT, and filed on Sep. 7, 2010 by inventors Magnus Goertz, Thomas Eriksson, Joseph Shain, Anders Jansson, Niklas Kvist and Robert Pettersson; and
- U.S. Provisional Patent Application No. 61/410,930, entitled OPTICAL TOUCH SCREEN SYSTEMS USING REFLECTED LIGHT, and filed on Nov. 7, 2010 by inventors Magnus Goertz, Thomas Eriksson, Joseph Shain, Anders Jansson, Niklas Kvist, Robert Pettersson and Lars Sparf.

U.S. patent application Ser. No. 13/052,511 is a continuation-in-part of:

- U.S. patent application Ser. No. 12/371,609, now U.S. Pat. No. 8,339,379, entitled LIGHT-BASED TOUCH SCREEN, and filed on Feb. 15, 2009 by inventors Magnus Goertz, Thomas Eriksson and Joseph Shain;
- U.S. patent application Ser. No. 12/760,567, entitled OPTICAL TOUCH SCREEN SYSTEMS USING REFLECTED LIGHT, and filed on Apr. 15, 2010 by inventors Magnus Goertz, Thomas Eriksson and Joseph Shain;
- U.S. patent application Ser. No. 12/760,568, entitled OPTICAL TOUCH SCREEN SYSTEMS USING WIDE LIGHT BEAMS, and filed on Apr. 15, 2010 by inventors Magnus Goertz, Thomas Eriksson and Joseph Shain.

U.S. patent application Ser. No. 12/760,567 claims priority benefit from U.S. Provisional Patent Application No. 61/169,779, entitled OPTICAL TOUCH SCREEN, and filed on Apr. 16, 2009 by inventors Magnus Goertz, Thomas Eriksson and Joseph Shain.

The contents of all of these applications are hereby incorporated by reference in their entireties.

FIELD OF THE INVENTION

The field of the present invention is light-based touch screens.

BACKGROUND OF THE INVENTION

Many consumer electronic devices are now being built with touch sensitive surfaces (track pad or touch screen), for use with finger or stylus touch user inputs. These devices range from small screen devices such as mobile phones and car entertainment systems, to mid-size screen devices such as notebook computers, to large screen devices such as check-in stations at airports.

In computing, multi-touch refers to a touch sensing surface's ability to recognize the presence of two or more points of contact with the surface. This plural-point awareness is often used to implement advanced functionality such as pinch to zoom or activating predefined programs (Wikipedia, "multi-touch"). The Windows 8 operating system from Microsoft Corporation requires a touch screen supporting a minimum of 5-point digitizers. WINDOWS® is a registered trademark of Microsoft Corporation.

The present invention relates to light-based touch sensitive surfaces. Light-based touch sensitive surfaces surround the surface borders with light emitters and light detectors to create a light beam grid above the surface. An object touching the surface blocks a corresponding portion of the beams.

Reference is made to FIG. **1**, which is a diagram of a prior art, light-based touch screen having 16 LEDs and 16 PDs. Screen **801** in FIG. **1** is surrounded by emitters **101** along two edges and photodiode (PD) receivers **201** along the remaining two edges, which together enable a lattice of light beams **300** covering the screen.

Light-based touch detection systems are unable to accurately recognize many instances of two or more points of contact with the surface. Reference is made to FIGS. **2** and **3**, which are illustrations of instances of ambiguous multi-touch detections in prior art touch screens. FIGS. **2** and **3** show different instances of two, diagonally opposed touches **901** and **902** that are ambiguous vis-à-vis the light grid of FIG. **1**. As shown in FIGS. **2** and **3**, the same light beams are blocked in both instances.

There is further ambiguity when more than two objects touch the screen simultaneously. Reference is made to FIGS. **4** and **5**, which are illustrations of instances of ghosted touches in prior art touch screens. The two-touch cases shown in FIGS. **2** and **3** are also ambiguous vis-à-vis the three-touch case, **901-903**, shown in FIG. **4**, and vis-à-vis the four-touch case, **901-904**, shown in FIG. **5**. In each of the cases illustrated in FIGS. **2-5**, row and column PDs a-h show an absence of light in the same locations. The ambiguity illustrated in FIGS. **4** and **5** is caused by "ghosting", which refers to an effect where the shadow of a first object obscures a second object and prevents the second object from being detected.

Light-based touch screens have many advantages over other touch sensor technologies such as capacitive and resistive solutions. Inter alia, light-based touch screens enable lower bill-of-materials cost than capacitive solutions, especially for large screens. Light-based touch screens are also superior to capacitive and resistive solutions in that a light-based touch screen does not require an additional physical layer on top of the screen that impairs the screen image. This is an important advantage for devices employing reflective screens where the brightness of the screen image depends on reflected light, rather than a backlight. Reference is made to U.S. Pat. No. 8,674,966 for ASIC CONTROLLER FOR A LIGHT-BASED TOUCH SCREEN, incorporated herein by reference in its entirety, which teaches faster scan rates for light-based touch screens than are available using prior art capacitive screens. It would be advantageous to provide a light-based touch screen that is operative to detect multi-touch gestures and that is compatible with the requirements of the Windows 8 operating system.

One drawback of prior art light-based touch screens is the need to accommodate the numerous light emitters and light detectors along all four edges of the screen. This requirement makes it difficult to insert light-based touch detection into an existing electronic device without significantly changing the layout of the device's internal components. It would be advantageous to reduce the number of components required and to enable placing them in a limited area rather than surrounding the entire screen. Reducing the total number of light emitters and light detectors required has the added benefit of reducing the bill-of-materials (BOM).

SUMMARY

Embodiments of the present invention provide unambiguous multi-touch detection based on blocked light beams. Other embodiments of the present invention provide 2D touch detection using a one-dimensional array of light emitters along only one edge of the screen and an opposite array of light detectors along the opposite edge of the screen.

There is thus provided in accordance with an embodiment of the present invention a rectangular arrangement of light emitters and light detectors, where light emitters are arranged along two adjacent edges of the rectangular arrangement and light detectors are arranged along the two remaining edges. Light from each emitter is detected by a plurality of the detectors. Each beam from an emitter to a detector traverses a plurality of screen pixels. A table stored in computer memory lists, for each beam, all of the pixels that lie in the beam's path. For each blocked beam, all of the pixels in the beam's path are marked as blocked; and for each non-blocked beam, all of the pixels in the beam's path are marked as unblocked. This creates a map with three types of pixels: fully blocked, fully unblocked and partially blocked. A partially blocked pixel is traversed by several beams, only some of which are blocked. A fully blocked pixel is traversed by several beams, all of which are blocked. The fully blocked pixels correspond to the touch locations. The system then connects adjacent blocked pixels to construct blobs of contiguous blocked pixels. Each blob, or set of contiguous blocked pixels, is treated as a single touch location.

There is additionally provided in accordance with an embodiment of the present invention a touchscreen featuring a row of light emitters along the bottom edge of the screen and a row of light detectors along the top edge of the screen. Each light emitter projects a very wide beam that is detected by all of the light detectors. The x-coordinate of an object touching the screen corresponds to a blocked beam that runs parallel to the side edges of the screen. The y-coordinate is determined by identifying the intersections between diagonal blocked beams.

There is further provided in accordance with an embodiment of the present invention a lens for placement opposite a diode in an optical touch sensor, including an upper portion including an upper refractive surface located nearer to the diode, and an upper reflector located further from the diode, the upper reflector being curved in two dimensions and cut horizontally by a top horizontal plane of the lens, and a lower portion, coplanar with the diode, including a lower refractive surface located nearer to the diode, and a lower reflector located further from the diode, the lower reflector being curved in the two dimensions and cut horizontally by a bottom horizontal plane of the lens, wherein the upper and the lower reflector are symmetrical and vertically aligned, and wherein non-collimated light reflected by the lower reflector onto the upper reflector is partially collimated in the two dimensions by the lower reflector and further collimated in the two dimensions by the upper reflector.

In cases where the lens' viewing angle of the diode is large, the height of the lens between the top and bottom horizontal planes is less than the height required for a curved reflector, cut vertically by a rear vertical backplane of the lens, to partially collimate and further collimate the non-collimated light.

There is yet further provided in accordance with an embodiment of the present invention a method a method for calculating multiple touch locations on a screen including activating a plurality of emitters and detectors around the perimeter of a screen, wherein each emitter-detector pair corresponds to a light beam crossing the screen, from among a plurality of such light beams, and wherein some of the light beams are blocked by one or more objects touching the screen, providing a look-up table listing, for each light beam from the plurality of light beams, other light beams from the plurality of light beams, that intersect that light beam, and their respective points of intersection, (a) identifying a first blocked light beam, (b) accessing the look-up table to identify a second blocked light beam that intersects the first blocked beam, (c) accessing the look-up table to identify intersection points of other blocked light beams that neighbor the intersection point of the thus-identified first and second blocked beams, (d) repeating operations (b) and (c) until all neighboring intersections points of blocked beams have been identified, and group the thus-identified neighboring intersections

as a single touch point, and (e) repeating operations (a)-(d) for remaining blocked light beams that were not yet grouped at operation (d).

There is moreover provided in accordance with an embodiment of the present invention a method for calculating multiple touch locations on a screen including activating a plurality of emitters and detectors around the perimeter of a screen, wherein each emitter-detector pair corresponds to a light beam crossing the screen, from among a plurality of such light beams, and wherein some of the light beams are blocked by one or more objects touching the screen, identifying the screen as an initial touch candidate region, for each candidate region: (a) identifying an unblocked light beam crossing that candidate region, (b) dividing that candidate region into multiple candidate regions, separated by the thus-identified unblocked light beam, and (c) repeating operations (a) and (b) for all unblocked beams, and designating the candidate regions whose sizes are larger than a minimum size, as being unique touch locations.

There is additionally provided in accordance with an embodiment of the present invention a method a method for calculating a touch location on a screen including providing a plurality of emitters and detectors around the perimeter of a screen, wherein each emitter-detector pair corresponds to a wide light beam crossing the screen, from among a plurality of wide light beams, activating a screen scan pairing each emitter with an opposite detector, (a) identifying those wide light beams, from the plurality of wide light beams, that are being blocked by an object touching the screen, (b) identifying an area of intersection between substantially perpendicularly oriented ones of the blocked wide beams identified at operation (a), (c) identifying additional blocked wide beams that cross the area of intersection identified at operation (b), (d) determining a degree of blockage for each additional blocked wide light beam identified at operation (c), (e) identifying two-dimensional shapes formed by the intersection of each additional blocked wide light beam identified at operation (c) with the blocked wide light beams identified at operation (a), and (f) calculating a weighted average of the centers-of-gravity of the thus-identified two-dimensional shapes, wherein each center-of-gravity's weight in the sum corresponds to its respective degree of blockage determined at operation (c).

There is further provided in accordance with an embodiment of the present invention a circular touch sensor including a housing, a surface mounted in the housing, including a circular portion exposed to receive touch input, a plurality of light detectors mounted in the housing along a semicircular contour corresponding to a half of the circular portion, wherein an angular pitch between neighboring detectors is constant, a plurality of light emitters mounted in the housing along an opposite semicircular contour corresponding to the opposite portion of the circular portion, and arranged in groups such that an angular pitch between neighboring emitters within each group is θ, and such that an angular pitch between nearest emitters in different groups is $\theta+a$, where a is positive, and a processor connected to the emitters and to the detectors, for synchronously co-activating emitter-detector pairs, and configured to calculate a two-dimensional location of an object touching the circular portion, based on outputs of the detectors.

There is yet further provided in accordance with an embodiment of the present invention a circular touch sensor including a housing, a surface mounted in the housing including a circular portion exposed to receive touch input, a plurality of light emitters mounted in the housing along a semicircular contour corresponding to half of the circular portion, wherein an angular pitch between neighboring emitters is constant, a plurality of light detectors mounted in the housing along an opposite semicircular contour corresponding to the opposite half of the circular portion, and arranged in groups such that an angular pitch between neighboring detectors within each group is θ, and such that an angular pitch between nearest detectors in different groups is $\theta+a$, where a is positive, and a processor connected to the emitters and to the detectors, for synchronously co-activating emitter-detector pairs, and configured to calculate a two-dimensional location of an object touching the circular portion, based on outputs of the detectors.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be more fully understood and appreciated from the following detailed description, taken in conjunction with the drawings in which:

FIG. **1** is a diagram of a prior art, light-based touch screen having 16 LEDs and 16 PDs;

FIGS. **2** and **3** are illustrations of instances of ambiguous multi-touch detections in prior art touch screens;

FIGS. **4** and **5** are illustrations of instances of ghosted touches in prior art touch screens;

FIG. **6** is an illustration of a network of intersecting light beams in a touch screen system, in accordance with an embodiment of the present invention;

FIG. **7** is an illustration of a network of intersecting light beams detecting five touch points in a touch screen system, in accordance with an embodiment of the present invention;

FIG. **8** is a flow chart describing a first method for identifying touch locations, in accordance with an embodiment of the present invention;

FIG. **9** is a flow chart describing a second method for identifying touch locations, in accordance with an embodiment of the present invention;

FIG. **10** is an illustration of neighboring intersections used by the method of FIG. **9**, in accordance with an embodiment of the present invention;

FIG. **11** is an illustration of a network of connected blocked beams used to locate a touch object, in accordance with an embodiment of the present invention;

FIG. **12** is an illustration of five identified touch objects identified by a touch screen, in accordance with an embodiment of the present invention;

FIGS. **13-18** are illustrations of an alternative method for determining touch locations, whereby portions of a large, candidate touch area are excluded based on unblocked thin light beams, in accordance with an embodiment of the present invention;

FIG. **19** is an illustration of five circles indicating areas though which no beams pass due to touch objects, in accordance with an embodiment of the present invention;

FIG. **20** is a graph tracking the number of separate touch candidate areas as a function of the number of unblocked beams, in accordance with an embodiment of the present invention;

FIGS. **21** and **22** are simplified illustrations of a partially blocked wide beam, that illustrate effects of where a blocking object is placed, in accordance with an embodiment of the present invention;

FIG. **23** is a simplified exemplary illustration of iso-curves across the width of a wide light beam, in accordance with an embodiment of the present invention;

FIGS. **24-30** are simplified illustrations of a method of touch location determination, whereby portions of a large, candidate touch area are excluded based on unblocked, and

partially blocked, wide light beams, in accordance with an embodiment of the present invention;

FIG. **31** is a simplified illustration of a partially blocked wide beam that extends between two adjacent screen edges, in accordance with an embodiment of the present invention;

FIGS. **32-34** are simplified drawings of an object being detected, in accordance with another method of the present invention, utilizing wide light beams;

FIG. **35** is a flowchart for a method of eliminating ghost touches, in accordance with an embodiment of the present invention;

FIG. **36** is a simplified drawing of a lens that distributes beams across many angles, in accordance with an embodiment of the present invention;

FIG. **37** is a simplified figure of four different fields of view that are all focused on a single diode, in accordance with an embodiment of the present invention;

FIG. **38** is a simplified illustration of the four fields of view of FIG. **37** as viewed from above, in accordance with an embodiment of the present invention;

FIGS. **39** and **40** are simplified illustrations of two beams from one emitter to two respective PDs, in accordance with an embodiment of the present invention;

FIGS. **41-43** are simplified illustrations of an arrangement of components, light guides, PCB and screen in a device, in accordance with an embodiment of the present invention;

FIGS. **44** and **45** are simplified illustrations of a light guide, in accordance with an embodiment of the present invention;

FIG. **46** is a simplified illustration of how microstructures correct the problem of gaps in the light field, in the light guide of FIGS. **44** and **45**, in accordance with an embodiment of the present invention;

FIGS. **47-49** are simplified illustrations of light guides, in accordance with an embodiment of the present invention;

FIG. **50** is a simplified illustration of a light intensity distribution across the width of a wide light beam, in accordance with an embodiment of the present invention;

FIG. **51** is a simplified illustration comparing light intensity distribution across the width of an un-reflected wide light beam with that of a wide beam that has passed through the light guide of FIGS. **44** and **45**, in accordance with an embodiment of the present invention;

FIGS. **52-54** are simplified illustrations of a light guide, in accordance with an embodiment of the present invention;

FIG. **55** is a prior art illustration of a light guide;

FIG. **56** is a simplified illustration of a light guide, in accordance with an embodiment of the present invention;

FIGS. **57** and **58** are simplified illustrations of a light guide arrangement for detecting touches and sweep gestures performed upon the light guide, in accordance with an embodiment of the present invention;

FIG. **59** is a simplified illustration of a touch screen having a row of emitters along the bottom edge of the screen and a row of receivers among the top edge of the screen, in accordance with an embodiment of the present invention;

FIG. **60** is a simplified illustration of the touchscreen of FIG. **59**, in accordance with an embodiment of the present invention;

FIG. **61** is an exploded view of the touchscreen of FIGS. **59** and **60**, in accordance with an embodiment of the present invention;

FIG. **62** is a simplified illustration of a touchscreen having a row of emitters along the bottom edge of the screen mounted on a first thin strip PCB and a row of receivers along the top edge of the screen mounted on a second thin strip PCB, in accordance with an embodiment of the present invention;

FIG. **63** is an exploded view of the touchscreen of FIG. **62**, in accordance with an embodiment of the present invention;

FIG. **64** is a simplified illustration of a foldable touchscreen, in accordance with an embodiment of the present invention;

FIG. **65** is a simplified illustration of a second foldable touchscreen, in accordance with an embodiment of the present invention;

FIG. **66** is a simplified illustration of light beams from one emitter reaching all of the detectors, in accordance with an embodiment of the present invention;

FIG. **67** is a simplified illustration showing which beams from FIG. **66** are blocked by an object touching the center of the screen, in accordance with an embodiment of the present invention;

FIG. **68** is a simplified illustration showing additional beams from other emitters that are not blocked by the object of FIG. **67**, in accordance with an embodiment of the present invention;

FIG. **69** is a simplified illustration showing all of the beams blocked by the object of FIG. **67**, in accordance with an embodiment of the present invention;

FIGS. **70-73** are illustrations of alternative LED and PD layouts for a circular touch surface, in accordance with alternative embodiments of the present invention;

FIG. **74** is an illustration of a light guide for a circular touch surface, in accordance with an embodiment of the present invention;

FIG. **75** is an illustration of a PCB layout for a circular touch surface, in accordance with an embodiment of the present invention;

FIG. **76** is an illustration of light beams emitted by one LED detected by a plurality of PDs surrounding a circular touch surface, in accordance with an embodiment of the present invention;

FIG. **77** is an illustration of a network of intersecting light beams used in a circular touch surface, in accordance with an embodiment of the present invention;

FIG. **78** is a simplified illustration of a circular touch surface sensor, in accordance with an embodiment of the present invention;

FIG. **79** is an illustration of the components used to assemble a circular touch surface, in accordance with an embodiment of the present invention;

FIG. **80** is an exploded view of the circular touch surface of FIG. **78**, in accordance with an embodiment of the present invention;

FIG. **81** is a cutaway view of the circular touch surface of FIG. **78**, in accordance with an embodiment of the present invention;

FIG. **82** is a simplified illustration of a light guide for the circular touch surface of FIG. **78**, in accordance with an embodiment of the present invention; and

FIGS. **83** and **84** are illustrations of paths of light beams used in a circular touch surface, in accordance with an embodiment of the present invention.

The following table catalogues the numbered elements and lists the figures in which each numbered element appears. Similarly numbered elements represent elements of the same type, but they need not be identical elements.

Numbered Elements

Element	Description	FIGS.
101-103	emitters	1-7, 32-34, 40, -42, 57, 58
104	LED chip	36, 38

-continued

Numbered Elements

Element	Description	FIGS.
105	plastic shell	36, 38
106-111	emitter	21, 22, 31, 39, 44-58, 61, 63, 66-69, 83, 84
201-203, 205-207	photodetector	1-7, 21, 22, 31-34, 39, 40, 50, 57, 61, 63, 66-69
210	photodetector chip	43
211	plastic shell	43
220	photodetector	83
300-306	light beam	1, 10, 14, 15
307, 308	blocked light beam	17, 18
311-314	intersection point	10
316-319	area q	30
320-326	light beam	21-26, 30, 31, 39, 40, 57, 58
327	iso-curve	24, 26
328	area q	24, 26
330	iso-curve	25, 26
331	area q	25, 26
332-335	light beam	27-30, 76, 83, 84
336	iso-curve	27, 29
337	area q	27, 29
338	iso-curve	28, 29
339	area q	28, 29
341	light beam	44, 45
342	gap	45
343-348, 354	light beam	44-48, 50
355-359	light intensity distribution	50, 51
360	light beams	59, 66-68
400	lens	36
401	entry surface	36, 38, 42, 43
402	exit surface	36, 38
403-407	lens	21, 22, 31, 39, 50
410	light guide frame	40, 57
411, 412, 416	light guide	41-46, 49, 51, 58
417	radius	46
419	viewing angle	46
420	refractive surface	45, 46
421	reflective surface	45, 46
422	refractive surface	45, 46
423	lens	45, 46
424	light guide	77-83
425	light shield	82
429	light guide	47
430	entry surface	47
431	exit surface	47
432	air gap	47
433	lens	47
440	light guide	48
441	reflective surface	48
442	refractive surface	48
443	air gap	48
444	lens	48
451	curved mirror	49
452	light guide	49
460	lens	52-54, 56
461	curved reflective surface	52, 54
462	curved reflective surface	52, 54
463	entry surface	52-54
464	exit surface	52-54
465	light beam	53, 54
466	upper lens portion	52, 54
467	lower lens portion	52, 54
470	light guide	55
471	curved reflective surface	55
472	height of parabola	55
473	reflector	55
474	bezel height	55
476	height for light channel	55
478	height	55
479, 480	light guide	59-65
481	backplane of light guide	55
482	depth of parabola	52
483	top horizontal plane	52, 54
484	bottom horizontal plane	52, 54
601-605	step in flowchart	8

-continued

Numbered Elements

Element	Description	FIGS.
612-614	screenshot	8
615-619	touch point	8, 19, 32
620-624	step in flowchart	9
630	screenshot	9
633-636	light beam	9
637-639	intersection point	9
640	screenshot	9
641-643	light beam	9
645-647	intersection point	9
650	screenshot	9
651	circle indicating touch area	9, 11
652	PCB	41-43, 58
653-656	candidate touch area (q)	13-18
657-659	PCB	60, 61, 63
660	screenshot	9
661	pcb	75, 79-81, 83
664-671	step in flowchart	35
701-705	touch point	12
710	controller	7
711	calculating unit	57
715	processor	75
801-803	screen	1-5, 13-19, 21, 22, 24-28, 32-34, 41-43, 49, 50, 58-68
804	crease	64, 65
810	touch plate	78-81, 83
811	top cover	78-81
812	bottom cover	78-81
900	arrow	58
901-904	touch point	2-5
905	touch object	21, 22, 31
906	rhomboid intersection area	33
910	touch object	67-69
911	screw	79-81
912	wire	78-80
913	haptic vibrator	79, 80

DETAILED DESCRIPTION

Aspects of the present invention relate to light-based touch screens and light-based touch surfaces. Throughout this specification, the terms "touch screen" and "touch sensitive surface" include touch sensitive electronic displays and touch surfaces that do not include an electronic display, inter alia, a mouse touchpad as included in many laptop computers and the back cover of a handheld device. They also include airspace enclosed by the rectangular emitter-detector sensor frame provided by the present invention.

According to embodiments of the present invention, a light-based touch sensor includes a plurality of infra-red or near infra-red light-emitting diodes (LEDs) arranged along two adjacent edges of a rectangular touch sensitive surface, as defined above, and a plurality of photodiodes (PDs) arranged along the two remaining adjacent edges. The LEDs project light collimated in height, in order to keep it parallel to the screen surface, but the light is spread out in a wide fan to reach many detectors. When this light is blocked by an inserted object, such as a finger or a stylus, the absence of expected light is detected by the PDs. The LEDs and PDs are controlled for selective activation and de-activation by a controller. Generally, each LED and PD has I/O connectors, and signals are transmitted to specify which LEDs and which PDs are activated. In some embodiments, each LED-PD pair is activated separately. In other embodiments, several PDs are activated concurrently during an LED activation.

Reference is made to FIG. **6**, which is an illustration of a network of intersecting light beams in a touch screen system, in accordance with an embodiment of the present invention.

FIG. **6** shows a first plurality of LEDs **102**, namely LED**0**-LED**15** along the top edge of a touch screen; a second plurality of LEDs **103**, namely LED**16**-LED**24** along the left edge of the touch screen; a first plurality of PDs **202**, namely PD**0**-PD**15** along the bottom edge of the screen; and a second plurality of PDs **203**, namely PD**16**-PD**24** along the right edge of the touch screen. FIG. **6** also illustrates all of the possible emitter-detector beams.

Reference is made to FIG. **7**, which is an illustration of a network of intersecting light beams detecting five touch points in a touch screen system, in accordance with an embodiment of the present invention. FIG. **7** shows the touch screen system of FIG. **6** detecting five touches in accordance with an embodiment of the present invention. The touches are indicated as solid black circles. The lines crossing the screen in FIG. **7** indicate unblocked emitter-detector beams. A controller **710** is shown for controlling activations of the emitters and detectors.

In some embodiments, each emitter has a respective collimating lens apart from the emitter, and each detector has a respective collimating lens apart from the detector. In some embodiments, these collimating lenses form a solid plastic frame along the borders of the rectangular touch screen. In other embodiments, these collimating lenses are absent to enable a wide, 180° spread angle of light beams from each emitter.

Different emitter-detector beams have different levels of detected intensity at their respective detectors. In an exemplary embodiment, 16 diodes are arranged along the screen length and 9 diodes are arranged along the screen width. TABLES I and II below list the detected intensity of unblocked beams from each emitter at each of detectors PD**0**-PD**15** along the screen length (TABLE I), and at each of the detectors PD**16**-PD**24** along the screen width (TABLE II). Empty cells indicate that no signal is detected for the corresponding emitter-detector beam.

TABLE II

Detected intensities of unblocked beams from each emitter at each of the 9 detectors along the screen width

	PD16	PD17	PD18	PD19	PD20	PD21	PD22	PD23	PD24
LED0									
LED1									
LED2	41	6							
LED3	49	25							
LED4	69	62							
LED5	44	44	15						
LED6	106	130	94	28					
LED7	96	139	165	235					
LED8	108	141	132	193	26				
LED9	125	154	169	236	153	17			
LED10	123	172	201	236	236	236			
LED11	27	45	117	236	236	236	98		
LED12				236	236	236	236	16	
LED13					103	236	236	235	72
LED14						39	236	236	235
LED15							49	236	235
LED16	236	171	166	170	162	164	142	142	160
LED17	236	209	206	235	233	222	204	219	233
LED18	180	201	164	166	179	170	147	169	192
LED19	197	224	200	209	187	165	151	199	236
LED20	191	214	193	198	187	170	167	194	213
LED21	235	235	234	232	212	187	173	211	222
LED22	204	215	215	226	202	192	188	209	198
LED23	197	201	217	234	209	201	173	170	169
LED24	188	183	164	180	129	118	99	99	192

The maximum detection intensity in TABLES I and II is 236. A detection intensity of at least 10 was found, by experiment, to be sufficiently greater than a noise signal, and therefore useful for detecting touches. In some embodiments, a threshold of ½ the expected intensity is used to determine whether a beam is blocked. Thus, if the expected intensity is 236, a detection signal below 118 renders the beam as blocked, whereas if the expected intensity is 49, a detection signal below 25 renders the beam as blocked.

TABLE I

Detected intensities of unblocked beams from each emitter at each of the 15 detectors along the screen length

	PD0	PD1	PD2	PD3	PD4	PD5	PD6	PD7	PD8	PD9	PD10	PD11	PD12	PD13	PD14	PD15
LED0	236	236	236	236	236	236	236	236	180	75	39	10				
LED1	236	236	236	236	236	236	236	236	236	179	101	68	23			
LED2	236	236	236	236	236	236	236	236	236	236	189	126	88	36	18	
LED3	236	236	236	236	236	236	236	236	236	236	236	174	114	47	32	7
LED4	236	236	236	236	236	236	236	236	236	236	236	234	164	100	62	25
LED5	236	236	236	236	236	236	236	236	236	236	236	236	217	122	75	25
LED6	236	236	236	236	236	236	236	236	236	236	236	236	236	236	184	117
LED7	236	236	236	236	236	236	236	236	236	236	236	236	236	236	236	162
LED8	236	236	236	236	236	236	236	236	236	236	236	236	236	236	236	234
LED9	184	169	236	236	236	236	236	236	236	236	236	236	236	236	236	236
LED10	139	132	165	236	236	236	236	236	236	236	236	236	236	236	236	236
LED11	84	75	100	195	235	236	236	236	236	236	236	236	236	236	236	236
LED12	47	49	96	205	236	236	236	236	236	236	236	236	236	236	236	236
LED13	4		15	90	122	194	236	236	236	236	236	236	236	236	236	236
LED14				57	75	162	197	236	236	236	236	236	236	236	236	236
LED15				26	45	97	148	236	236	236	236	236	236	236	236	236
LED16	236	236	44													
LED17	236	236	236	61	12											
LED18	145	236	236	236	183											
LED19	10	50	236	236	236	236	59									
LED20			72	236	236	236	236	77	13							
LED21			4	178	236	236	235	153	120	18						
LED22				1	236	216	177	160	134	70	23					
LED23					57	149	180	159	149	84	49	32	1			
LED24					29	195	200	183	171	86	61	51	30	14	26	

In addition, certain beams were found to continue being detected even when the entire screen was blocked. These beams, situated at corners of the touch screen, do not need to cross the screen area in order to arrive at their respective detectors. TABLE III lists the detection values registered when the entire rectangular touch screen area is covered by a solid opaque object.

TABLE III

Detected intensities of blocked beams

LED	PD 0	PD 1	PD 2	PD 3	PD 4	...	PD 15	PD 16	PD 17	PD 18	PD 19	PD 20	PD 21	PD 22	PD 23	PD 24
0																
1																
2																
3																
4																
5																
6																
7																
8																
9																
10																
11																
12																
13																
14																235
15														44	235	235
16	236	236	40													
17	236															
18	135															
19	8															
20																
21																
22																
23																
24																

35

TABLE IV lists with an 'x' the useful beams in this exemplary embodiment by including beams from TABLES I and II having an unblocked detection value of at least 10, and excluding the beams detected in TABLE III.

TABLE IV

Usable detection beams

	PD 0	PD 1	PD 2	PD 3	PD 4	PD 5	PD 6	PD 7	PD 8	PD 9	PD 10	PD 11	PD 12	PD 13	PD 14	PD 15	PD 16	PD 17	PD 18	PD 19	PD 20	PD 21	PD 22	PD 23	PD 24
LED0	X	X	X	X	X	X	X	X	X	X	X	X													
LED1	X	X	X	X	X	X	X	X	X	X	X	X	X												
LED2	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X								
LED3	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X							
LED4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X							
LED5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
LED6	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					
LED7	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					
LED8	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				
LED9	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			
LED10	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			
LED11	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
LED12	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	
LED13			X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	X	X	X	X
LED14				X	X	X	X	X	X	X	X	X	X	X	X	X						X	X	X	
LED15				X	X	X	X	X	X	X	X	X	X	X	X	X									
LED16																	X	X	X	X	X	X	X	X	X
LED17		X	X	X	X												X	X	X	X	X	X	X	X	X
LED18		X	X	X	X												X	X	X	X	X	X	X	X	X
LED19		X	X	X	X	X	X										X	X	X	X	X	X	X	X	X
LED20			X	X	X	X	X	X	X								X	X	X	X	X	X	X	X	X
LED21				X	X	X	X	X	X	X							X	X	X	X	X	X	X	X	X
LED22					X	X	X	X	X	X	X						X	X	X	X	X	X	X	X	X

TABLE IV-continued

	Usable detection beams																								
	PD 0	PD 1	PD 2	PD 3	PD 4	PD 5	PD 6	PD 7	PD 8	PD 9	PD 10	PD 11	PD 12	PD 13	PD 14	PD 15	PD 16	PD 17	PD 18	PD 19	PD 20	PD 21	PD 22	PD 23	PD 24
LED23					X	X	X	X	X	X	X	X					X	X	X	X	X	X	X	X	X
LED24					X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X

Touch Coordinate Method

This section describes in detail the operations to determine a tracked object's location. Reference is made FIG. **8**, which is a flow chart describing a first method for identifying touch locations, in accordance with an embodiment of the present invention. FIG. **8** shows a first method for calculating touch positions. At step **601** the touch sensitive area is parsed into a two-dimensional (2D) pixel or cell grid. In addition, a table is generated storing a list of pixels or cells traversed by each active detection beam marked in TABLE IV. In some embodiments, the table is stored as a list of pixel entries, each pixel entry storing a list of beams that pass through the pixel. In other embodiments, the table is stored as a list of light beam entries, each light beam entry storing a list of pixels along its beam path. Step **601** is performed offline. In some embodiments, the cells are of different sizes depending on location. For example, at the center of the screen the cells are smaller corresponding to the high density of beams vis-à-vis cells near the edges of the screen where the density of beams is lower. In some embodiments, the cells are not aligned along a two dimensional grid. Rather, each cell surrounds a point of intersection between two beams.

At step **602** a scan is performed for all usable beams listed in TABLE IV. Each beam is marked as either blocked or unblocked, according to a detection threshold, as described hereinabove. Screenshot **612** illustrates the unblocked beams in a case of five simultaneous touches.

At step **603** each pixel in the 2D cell grid from step **601** receives a binary value (blocked=1/not blocked=0). This binary value is a logical AND between all of the binary values from step **602** of LED-to-PD light beams that pass through the cell, according to the stored list from step **601**. Thus, in this method unblocked beams are used to mark cells as untouched. A single, unblocked beam passing through a grid cell is sufficient to mark the cell as untouched. According to an alternative method described below intersectionsofblockedbeams are used to fill the grid from step **601**. Screenshot **613** illustrates cells marked as untouched (white) and touched (black).

At step **604** touch areas are formed by connecting neighboring blocked grid cells: for each pixel in step **603** having a value of 1 (blocked), four immediate neighbors are checked, namely, top, bottom, left and right neighbors. Any neighbor having a value of 1 is connected. Screenshot **614** illustrates five touch locations **701-705** identified by joining connected neighbors.

At step **605** the touch coordinates and area of each touch location are calculated. In some embodiments, the area of a touch location is the sum of its pixels and the touch position is the center of gravity of the area. In some embodiments, a valid touch location must have a minimum area, e.g., based on the expected size of a finger. Furthermore, in some embodiments a maximum size for a touch object is also provided. When a touch area exceeds the maximum size it is either discarded or it is assumed to contain multiple objects placed together on the screen. Thus, the touch sensor is operable to distinguish between a single finger performing a gesture and multiple fingers placed together performing the same gesture. Similarly, when the system tracks multiple touch objects, the system is operable to continue tracking them as multiple objects even after they are brought together based on the large size of the touch object, e.g., in a pinch gesture.

Reference is made to FIG. **9**, which is a flow chart describing a second method for identifying touch locations, in accordance with an embodiment of the present invention. At step **620** a lookup table of intersection points between light beams is generated. In this table, every entry includes, for each light beam of the usable light beams listed in Table IV, other beams that intersect that beam and their respective points of intersection, and for each point of intersection the lookup table includes pointers to four neighboring intersection points, namely two immediate neighboring intersection points along each of the two intersecting beams. These neighboring intersection points are illustrated in FIG. **10**.

Reference is made to FIG. **10**, which is an illustration of neighboring intersections used by the method of FIG. **9**, in accordance with an embodiment of the present invention. FIG. **10** shows two primary intersecting beams **301**, **302** intersecting at point **310**. Two additional beams, **303**, **304**, also intersect beams **301**, **302** at points **311-314**. The lookup table entry for intersection point **310** includes the coordinates of point **310** and pointers to neighboring intersection points **311-314**.

Returning to FIG. **9**, at step **621** all usable beams, as listed in TABLE IV, are scanned and assigned a binary blocked/unblocked value by comparing the beam's detection value to a threshold. In some embodiments, a normalized detection value is used instead of a binary value; the normalized values from neighboring beams are then interpolated to refine the touch location calculation.

At step **622** blocked beams are analyzed in the following manner. When a first blocked beam is identified, the method checks every intersection point along the blocked beam to see if that point is an intersection of twoblocked beams. When such an intersection point is identified, the method recursively checks all immediate neighboring intersection points for additional intersections of two blocked beams until no further intersection points of two blocked beams are found. All neighboring intersection points that are also formed by two blocked beams are assumed to belong to the same touch object and are therefore grouped together. This recursive method finds all of the connected intersections belonging to a single touch object. The method is then repeated beginning with a blocked beam not already used in the previous steps. The resulting network of connected intersection points, where pairs of blocked beams intersect, is illustrated inside circle **651** in FIG. **11**.

Reference is made to FIG. **11**, which is an illustration of a network of connected blocked beams used to locate a touch object, in accordance with an embodiment of the present invention. FIG. **11** shows blocked and non-blocked beams in a case of one touch. FIG. **11** is a color figure. Green lines represent non-blocked beams and red lines represent blocked beams. Thus, a significant intersection point is a point at

which two red lines intersect. From a first such red intersection point, the current method recursively builds a network of connected red intersections. This area is the red area marked in FIG. **11** by yellow circle **651**.

Step **622** is illustrated by frame **640** in FIG. **9**. Frame **640** includes a first blocked beam **633**. Three intersection points **637-639** along beam **633** are shown. Points **637** and **638** are where beam **633** intersects two non-blocked beams, **634** and **635**, respectively. Point **639** is an intersection between beam **633** and a second blocked beam **636**. Intersecting beam **636** is the second blocked beam identified by this method.

At step **623** the method recursively checks intersection points neighboring point **639** to create a network or web of neighboring intersections that belong to the same touch object. This is illustrated in FIG. **9** by frame **650**, showing first intersection point **639** and neighboring intersection points **645-647**. Point **647** is the next intersection point along beam **633**; points **645** and **646** are neighboring intersections along second blocked beam **636**. Point **645** is where beam **636** meets beam **643**, and point **646** is where beam **636** meets beam **641**. The recursive nature of this step means that if any of these points **645-647** are also formed by two blocked beams, the search expands to their neighbors. The list of neighboring intersections is generated offline and stored in memory. The method begins by sequentially checking the beams. The first blocked beam branches the search to check its neighbors. A list of checked beams is used to avoid checking neighbor beams again when the method resumes sequentially checking for a first blocked beam.

At step **624** the method proceeds to analyze the connected intersection points to extract the first and last blocked intersection point on each beam. This provides an outline of the touch area. Thus, in FIG. **11**, these outermost points form yellow circle **651** that surrounds the network, or web, of red lines. A miniaturized version of FIG. **11** is presented in frame **660** in FIG. **9**, with yellow circle **651** surrounding the web of red beams. The touch location is calculated as the average of these two endpoints for all beams. The width and height of the touch area are calculated by determining the area's left, right, top and bottom coordinates. These are determined by the maximum and minimum coordinates of intersection points in each direction, or alternatively, by averaging the coordinates of two or three maximum and minimum intersection points in each direction.

If a candidate touch location includes at least one unique blocked beam, i.e., if a blocked beam that does not pass through any other candidate touch locations, then it is confirmed to be an actual touch location. If no unique blocked beam corresponds to a candidate touch location, i.e., if all blocked beams passing through the candidate location pass through at least one other confirmed touch location, then that candidate touch location is discarded. In this way phantom touches, i.e., locations corresponding to intersections of blocked beams that are not generated by an object at the intersection location, but rather by two objects that cast a light-beam shadow on that location, are discarded.

Reference is made to FIG. **12**, which is a map of locations at which detection beams intersect. As explained hereinabove, intersections for which every intersecting beam is blocked is marked as a blocked intersection. Blocked intersections are shaded black in FIG. **12**. FIG. **12** shows five clusters of blocked intersections **701-705** corresponding to five touch objects identified by the system and methods described hereinabove. Additional blocked intersections are shown, but they belong to clusters too small to quality as touch objects.

Reference is made to FIGS. **13-18**, which are illustrations of an alternative method for determining touch locations, whereby portions of a large, candidate touch area are excluded based on unblocked thin light beams, in accordance with an embodiment of the present invention. The method uses very thin beams and assumes that any object touching the screen has a radius of at least d. The method begins by defining the entire screen as a potential touch area Q in which touch objects of radius d may be present. FIG. **13** shows a screen **802** with area Q indicated by shaded area **653**. An unobstructed narrow beam indicates that no object having radius d is located within a distance d from the beam. This situation is illustrated in FIG. **14** showing unobstructed, narrow beam **305** passing across screen **802**. Based on the assumption that any touch object has a radius d, it is evident that no such touch object is located within distance d of beam **305**. Therefore a corridor having a width of 2d along beam **305** is removed or excluded from Q, splitting Q into two polygons **653** and **654**. As more unobstructed beams are added, more areas are removed from Q. Thus, in FIG. **15** two unobstructed beams **305** and **306** are shown, whereby Q is divided into four polygons **653-656**. Eventually, Q becomes an increasing number of separate, convex polygons, with an increasing number of edges, as illustrated in FIG. **16**, where Q has been reduced to three convex polygons **653-655**. When implementing this method it is sometimes advantageous to advance through neighboring beams rather than distant beams. For example, referring back to FIG. **15**, it can be seen that a second unblocked beam alongside beam **305** would reduce the size of Q without adding any additional polygons, whereas in FIG. **16** unblocked beam **306** adds two new polygons **355** and **356**. Additional polygons in Q require, inter alia, more memory to store the additional polygon data.

In some implementations, the method does not proceed beyond dividing Q based on unblocked narrow beams. The method ends when all unblocked beams have been analyzed. Each remaining polygon in Q is assumed to contain a touch object, but the object's location within the polygon is unknown. Reference is made to FIG. **16** showing three polygons **653-655** remaining in Q, and thus three objects are assumed to be touching screen **802** at these three locations, respectively. In some embodiments each polygon's center of gravity is assumed to be center of its respective touch object.

Certain touch patterns will generate more separate polygons in Q than touch points. These extra polygons are known as ghost points. One way of disambiguating or eliminating ghost points is to continue the method with a second step of analyzing blocked beams, as explained with reference to FIGS. **17** and **18**. Each blocked beam i indicates a region O_i along the beam containing at least one touch object with radius d. Since touch objects can only exist in Q, there is at least one object where O_i intersects Q, i.e., $O_i \cap Q \neq \emptyset$. FIG. **17** shows blocked beam **307**. Two polygons in Q lie within a distance d from the path of this beam, namely, polygons **654** and **655**, and both polygons are equally likely to contain the blocking object. In order to resolve this ambiguity, only polygons in Q having a unique blocked beam, i.e., the blocked beam passes through only one polygon in Q, are assumed to contain a touch object. FIG. **18** shows a second blocked beam **308**. Only one polygon in Q lies within a distance d from the path of this beam, namely, polygon **655**. Therefore, polygon **655** definitely contains a touch object. Polygon **654** may contain an additional touch object, or it may be a ghost point. In cases when multiple objects are being tracked, polygons in Q crossed by non-unique blocked beams that seem to correspond to a tracked object are assumed to contain the tracked object. Thus, if the location of **654** corresponds to a previ-

ously tracked touch object, polygon **654** is assigned a touch object, but otherwise it is ignored as a ghost point.

The center of an assumed touch object is the center of gravity of its polygon Q. Alternatively, the center of an assumed touch object is the center of gravity of the polygon defined by $O_i \cap Q$, which may be smaller than polygon **654**. Thus, polygons in Q traversed by a unique blocked beam definitely contain a touch object, whereas polygons in Q not traversed by a unique blocked beam but only by blocked beams that traverse multiple polygons in Q possibly contain a touch object. In some embodiments, these possible touch candidates are reported as possible, not definite, touch locations.

Reference is made to FIG. **19**, which is an illustration of five circles **615-619** indicating areas though which no beams pass due to touch objects, in accordance with an embodiment of the present invention. Using the method illustrated in FIGS. **13-18**, area Q inside each circle is the resulting touch candidate area. Thus, five touch objects are identified using only the unblocked beams shown in FIG. **19**.

Reference is made to FIG. **20**, which is a graph tracking the number of separate touch candidate areas as a function of the number of unblocked beams, in accordance with an embodiment of the present invention. The x-axis represents the number of beams analyzed in a touch system, and the y-axis represents the number of individual polygons identified in Q. After analyzing 150 beams, six separate polygons are identified in Q. However, once 250 beams have been analyzed, one of the polygons was eliminated because some of the unobstructed beams 150-250 passed within d of the sixth polygon, removing it from Q.

In order to detect a touch object, having an assumed minimum diameter d, anywhere on the screen, every location on the screen must be within a distance d of at least one beam. Therefore, any area not within a distance d of at least one beam is identified and removed from Q. Put another way, any area farther than d from all beams is an undetectable area R. Any area common to Q and R, namely, $R \cap Q$, is a blind area. Such areas are defined by the beam layout and by the size of d and should be masked out of Q as it is not possible to determine if an object will be present there.

A variation of the method that excludes portions of area Q based on unblocked beams is now described. The method described above uses narrow beams, such that a beam is either blocked or unblocked, i.e., each beam has a binary state. The variation uses wide beams that can be partially blocked. In the case of wide beams an amount of blockage is used to determine where within the beam the blocking object may be located and excluding the remaining portion of the beam from Q.

Reference is made to FIGS. **21** and **22**, which are simplified illustrations of a partially blocked wide beam, that illustrate effects of where a blocking object is placed, in accordance with an embodiment of the present invention. FIG. **21** shows beams of light **323** and **324** exiting from an extended emitter lens **404** and arriving at an extended receiver lens **403**. A wide beam from emitter **106** passing through lens **404** to receiver **206** via lens **403** can be simulated as a series of point-source beams originating along lens **404**, each point-source beam spreading to cover receiver lens **403**. Two such beams are shown in FIG. **21**, namely beams **323** and **324**. In FIG. **21**, touch object **905** blocks a portion of these beams from reaching the left edge of receiver lens **403**. The method assumes that any blocking object, e.g., pointer **905**, has a radius of at least d and that the object blocks the beam from one of the beam's edges inward. Thus, the amount of expected light that is absent at receiver **206** indicates the extent that a touch object of radius d has entered this beam. FIG. **21** illustrates beam blockage when object **905** is inserted mid-way between lenses **404** and **403**. Greater amounts of light are blocked when object **905** is inserted nearer to either lens **404** or lens **403** and object **905** is inserted less than half-way through the beam.

FIG. **22** shows object **905** inserted near emitter lens **404**, and its effect on simulated point-source beams **323** and **324**. In this case the total amount of detected light at receiver **206** is less than the amount detected in the case of FIG. **21**, even though object **905** is inserted to the same extent through the wide beam (from lens **404** to lens **403**). A similar amount of light is detected when object **905** is inserted near lens **403**.

Thus, when an object having a radius d blocks a portion of a wide beam, the portion extending from the side of the beam inward, the outer edge of the object must be somewhere along a curve within the beam. Beam light intensities for all possible touch points of an object with radius d are calculated numerically using the model illustrated by FIGS. **21** and **22**.

Reference is made to FIG. **23**, which is a simplified exemplary illustration of iso-curves across the width of a wide light beam, in accordance with an embodiment of the present invention. FIG. **23** shows the result of the above calculation displayed as a set of solid curves. The dashed curves are an approximation using a least squares fit polynomial. The solid and dashed curves are referred to as "iso-curves" (iso means equal). Thus, if the outer edge of the touch object is anywhere along an iso-curve the amount of light detected is the same.

In some embodiments of the present invention, the iso-curves are measured on the device. This is particularly suitable for systems that employ complex light guides in which the light intensity distribution across the width of the wide beam is not a simple curve, such as the light guide illustrated in FIG. **44**, as explained below with reference to FIG. **51**. In other embodiments of the present invention, the iso-curves are calculated as follows. When the beam is obstructed from the left to some edge (x, y), light emitted from position a on the source will shine on the sensor from the projection of the edge β_0, to the right edge of the sensor. Integrating the lit up ratio of the sensor over all emitting positions gives the total detected light intensity from the sensor. Left to right for x, a and β_0 range from 0 to 1, and y—the coordinate along the beam from source to sensor, also ranges from 0 to 1. The formulas for calculating the intensity ratio I are given by Equations (1) and (2):

$$\beta_0(x, y, \alpha) = \begin{cases} 1, & \gamma > 0 \\ 0, & \gamma < 0 \\ \gamma, & \text{otherwise} \end{cases}, \quad (1)$$

$$\gamma = \alpha - \frac{x - \alpha}{y}$$

$$I = \int_{\alpha=0}^{1} 1 - \beta_0(x, y, \alpha)\, d\alpha \quad (2)$$

In some embodiments of the present invention, the iso-curves are measured on the device and added as a multiplier along with a and β_0.

FIG. **23** illustrates a plurality of iso-curves in wide beam **325** representing steps of 5% of the unobstructed light intensity. Thus, the leftmost curve represents the possible locations of the object's outer edge when 5% of the intensity of beam **325** is blocked, the second from left represents 10% blocked intensity, etc. The iso-curves marking the possible object edge on the right half of beam **325** are a mirror reflection of

the iso-beams on the left half of beam **325**. Although FIG. **23** illustrates specific iso-curves, they are not quantum steps, as evidenced by Equations (1) and (2) above. Rather, the iso-curves progress linearly across the entire width of beam **325** and the illustrated curves in FIG. **23** are merely examples.

Conceptually, each iso-curve is the equivalent of a thin beam in the previous method. That is, in the previous method, an unblocked thin beam means that the object of radius d was at least a distance d away from the beam path. Similarly, when for example 20% of wide beam **325** is blocked, that means that, with reference to the iso-curves in FIG. **23**, the edge is somewhere along the fourth iso-curve from the left, or the fourth iso-curve from the right. The object cannot be right of the fourth-from-left iso-curve or to the left of the fourth-from-right iso-curve and thus these areas are removed from Q. Moreover, because the method is searching for the center coordinates of the touch object, a margin of width d along these iso-curves can further be removed from Q. This process is explained with reference to FIGS. **24-30**.

Reference is made to FIGS. **24-30**, which are simplified illustrations of a method of touch location determination, whereby portions of a large, candidate touch area are excluded based on unblocked, and partially blocked, wide light beams, in accordance with an embodiment of the present invention. FIG. **24** shows the center **326** of a partially blocked wide beam crossing the screen. The amount of expected light missing from this wide beam is less than 50%; i.e., more than 50% of the beam's light was detected. A corresponding iso-curve **327** is shown to the left of center **326** indicating a border along which the object blocking this beam may be located. The object may be located anywhere to the right of iso-curve **327**, but it cannot extend to the left beyond this iso-curve. Thus the area covered by this wide beam and left of iso-curve **327** can be removed from Q, assuming the object entered the beam from the beam's right edge. Moreover, because the method seeks the coordinates of the center of the object, a margin of width d to the right of iso-curve **327** can be further removed from Q. The area remaining in Q is area **328**.

FIG. **25** shows center **326** of the same beam as in FIG. **24**, but shows how Q is reduced when the object was inserted into this wide beam from the left. The corresponding iso-curve **330** is shown, to the right of which, the object cannot be located. And an additional margin having width d is shown along iso-curve **330** inside which the center of the object cannot be located. The area thus remaining in Q is shaded area **331**.

FIG. **26** shows the areas **328** and **331** remaining in Q (in screen **802**) based on this partially detected wide beam. Thus, areas **331** and **328** are convex, as a result of the fact that more than 50% of the wide beam was detected, in other words, less than 50% of the beam was blocked. When less than 50% of the wide beam is detected, the resulting areas in Q are concave, as explained below.

FIG. **27** shows the center **335** of a wide horizontal beam that is partially blocked. In this case, more than 50% of the beam is blocked, i.e., less than 50% of the expected light for this beam was detected. As above, it is unknown from which side of the beam the object entered the beam. FIG. **27** shows shaded area **337** as the remaining area Q if the object was inserted into the beam from below. In this case, iso-curve **336** is the curve along which the outer edge of the object may lie. It is noted that because the object is assumed to have been inserted from the bottom of the beam, and blocks more than 50% of the wide beam's light, the object is assumed to cover center **335** of this beam and iso-curve **336** is therefore above center **335**. The object cannot extend upward of iso-curve **336** and therefore this area within the wide beam is removed from Q. Also, because this method searches for the center of the object, a margin of width d, the assumed radius of the object, below iso-curve **336** can also be removed from Q. Thus, the area remaining in Q is shaded area **337**.

FIG. **28** shows how much remains in Q when it is assumed that the object enters the beam from above. FIG. **28** shows the center **335** of the beam, iso-curve **338** below center **335**, and shaded area **339** remaining in Q. The border of area **339** is offset a margin d from iso-curve **338**.

FIG. **29** shows the area remaining in Q after analyzing this horizontal beam that is mostly blocked, by combining the results of FIGS. **27** and **28**. Areas **337** and **339** remaining in Q are concave.

FIG. **30** shows a map of remaining areas Q after combining the analyses of the beams in FIGS. **26** and **29**. Q is now made up of four separate areas **316-319**.

Although the illustrated wide beams span an area between opposite sides of screen **802**, this method also applies to beams that span an area between adjacent screen edges. Reference is made to FIG. **31**, which is a simplified illustration of a partially blocked wide beam that extends between two adjacent screen edges, in accordance with an embodiment of the present invention. FIG. **31** shows a diagonal beam extending from a bottom edge to the right edge of the screen. The wide beam generated by LED **106** and emitter lens **404** terminates at receiver lens **403** which directs the beam to receiver **206**. An object **905** is blocking a portion of the beam. Two simulated point-source beams **323** and **324** are shown, similar to those in FIGS. **21** and **22**. Based on the calculations described hereinabove, a set of iso-curves is calculated for this beam to map possible edges of an object according to the amount of the beam that is blocked.

Reference is made to FIGS. **32-34**, which are simplified drawings of an object being detected, in accordance with another method of the present invention, utilizing wide light beams. In some embodiments of the present invention, opposing rows of emitters and receivers are used, each emitter being opposite a respective receiver, whereas in other embodiments of the present invention the emitters are shift-aligned with the receivers. For example, each emitter may be positioned opposite a midpoint between two opposing receivers, or each emitter may be off-axis aligned with an opposite receiver, but not opposite the midpoint between two receivers. In addition, certain embodiments employ collimating lenses coupled with a surface of micro-lenses that refract light to form multiple wide divergent beams. A discussion of these different embodiments is included in co-pending U.S. Pat. No. 8,674,966 entitled ASIC CONTROLLER FOR LIGHT-BASED TOUCH SCREEN, incorporated by reference hereinabove. Once touch locations have been determined using any of the systems and methods described in U.S. Pat. No. 8,674,966, the present application teaches how to resolve possible ghost touches.

FIG. **32** shows touch location **616**, the initial location of which on the horizontal axis of screen **802** is determined based on a weighted sum of two detection signals: the partially blocked beams from emitter **101** to receiver **201**, and from emitter **101** to receiver **202**. That is, the beams from emitter **101** to receiver **201** and from emitter **101** to receiver **202** are wide beams and each beam has a respective coordinate value along the horizontal axis of screen **802**, X_a and X_b. The coordinate value associated with each beam is assigned a weight W, corresponding to the amount of light blocked from that beam by the object at location **616**. The location is thus determined using the weighted average

$$X_P=(W_aX_a+W_bX_b)/(W_a+W_b), \quad (3)$$

where the weights W_a and W_b are normalized signal differences for the two beams.

If the pointer is detected by more than two emitter-receiver pairs, then the above weighted average is generalized to

$$X_P=\Sigma(W_nX_n)/(\Sigma W_n), \quad (4)$$

where the weights W_n are normalized signal differences, and the X_n are weight positions. These calculations are described in U.S. Pat. No. 8,674,966, with reference to FIGS. 137 and 143-150 therein, based on an initial assumed Y axis coordinate of the touch. Thus, both an X-coordinate and a Y-coordinate are determined initially. For the sake of exposition, the beams crossing screen **802** in a vertical direction, e.g., beams **101-201** and **101-202**, are referred to as vertical wide beams, and beams crossing screen **802** in a horizontal direction, e.g., beams between emitters and receivers along the left and right sides of screen **802**, are referred to as horizontal wide beams.

In order to refine the touch coordinate further and resolve any possibility that this determined location is actually a ghost point, a second set of calculations is performed. The first step in this second process is to assemble a list of all of the vertical wide beams that contributed to the X coordinate calculation, e.g., beams **101-201** and **101-202** in the example of FIG. **32**. For each vertical wide beam in this list, a secondary list is compiled of all wide beams from any emitter on the right side of the screen to any receiver on the left of the screen that crosses the determined location. FIG. **33** shows two intersecting wide beams: vertical wide beam **101-201** and horizontal wide beam **102-203**. The secondary list of wide beams crossing beam **101-201** and also covering coordinate **616** is illustrated in FIG. **34**. A similar secondary list is compiled for wide beams crossing beam **101-202** and also covering coordinate **616**.

Thus, numerous pairs of intersecting beams are identified in which the intersection covers the determined location. Each such intersection between two wide beams forms a two-dimensional shape, such as rhombus **906** in FIG. **33**. The center of gravity of each rhombus is used as a coordinate in calculating a weighted sum to refine the touch location. However, if any of the intersecting beams in the secondary list is entirely unblocked, it is evident that the current touch location is a ghost touch, not a real touch.

When all of the intersecting beams in the secondary list are at least partially blocked, the touch location is refined by calculating a weighted sum using the center of gravity of each rhomboid intersection area multiplied by a weight corresponding to the degree to which that rhomboid's intersecting horizontal beam is blocked. In some embodiments, the weight corresponds to the degree to which both of that rhomboid's intersecting beams are blocked—i.e., both the vertical beam and the horizontal beam.

This process is repeated for the Y coordinate calculation, using horizontal beams that contribute to the initial Y coordinate calculation. In this case, the secondary list for each horizontal wide beam includes wide beams from any emitter along the top edge of the screen to any receiver along the bottom edge of the screen that covers the initial touch location.

Reference is made to FIG. **35**, which is a flowchart for a method of eliminating ghost touches, in accordance with an embodiment of the present invention. At step **664**, an initial set of possible touch coordinates is calculated using only vertical and horizontal light beams, but not diagonal beams. In systems in which the emitters are shift-aligned with the receivers, only shift-aligned emitter-receiver pairs are used. This includes divergent pairs of beams from one emitter to two receivers.

Step **665** is a loop that iterates over each touch candidate calculated in step **664**. Step **666** is a loop over the x and y coordinates of each touch candidate. The body of this inner loop is steps **667-671**.

At step **667** the system compiles a list of all beams that cross one of the beams used in step **664** and also traverse the coordinate calculated in step **664**. In some embodiments this is done by consulting a look up table. In other embodiments, calculations are used to compile this list.

At step **668** the system checks whether any of these incident beams is completely unblocked. If any of these beams is completely unblocked, the candidate touch location is determined to be a ghost point (step **669**) and the system advances to the next touch candidate.

If all of the beams at step **668** are partially blocked, the system refines the touch coordinate by calculating a weighted sum of all of the incident beams crossing this touch location. The rhomboid area of overlap between each of the wide beams used in step **664** and each of the wide beams identified in step **667** is calculated at step **670**. Then the center of gravity of this area is calculated, and the center of gravity's coordinate along the desired axis is used in the weighted sum. A respective weight is assigned to each center of gravity according to the degree to which the incidental beam is blocked. The refined touch coordinate is a weighted sum of all the center-of-gravity coordinates along the desired axis, calculated at step **670**. This weighted sum is calculated at step **671**.

Lenses

In some embodiments of the invention each LED and each PD is coupled with a lens. This section explains several lens structure alternatives that maximize the amount of light utilized for touch detection.

A first lens is acylindrical, with a progressive focal length, in order to keep good focus on the associated LED or PD chip for all angles. Reference is made to FIG. **36**, which is a simplified drawing of a lens that distributes beams across many angles, in accordance with an embodiment of the present invention. FIG. **36** is a view from above, showing an LED chip **104** emitting light beams through its plastic shell **105** and into lens **400** of the present invention. Lens **400** has a curved entry surface **401** and a flat exit surface **402**. Four beams are shown exiting the lens at angles of 0°-60°. However, a continuous array of beams exits along the lens exit surface **402**, and their angles gradually increase along the exit surface **402**. The curvature of entry surface **401** is optimized for this progression of exit angles. Entry surface **401** is only curved in the plane perpendicular to the screen, and thus has no optical power in the plane of the screen.

Reference is made to FIG. **37**, which is a simplified figure of four different fields of view that are all focused on a single diode, in accordance with an embodiment of the present invention. FIG. **37** is composed of four side views of fields of collimated beams each entering the light guide at a different angle, namely the same angles shown in the FIG. **36** view from above. Despite these different angles, FIG. **37** shows how all four fields are focused on the diode chip, despite their largely varying effective focal lengths.

Reference is made to FIG. **38**, which is an illustration of the four fields of view of FIG. **37** as viewed from above, in accordance with an embodiment of the present invention. FIG. **38** shows a short focal length f**0** for 0° and a long focal length f**60** for 60°. The same numbered elements represent the same objects, in FIGS. **36** and **38**. Although lens **400** is described with reference to LED **104**, identical lenses are used for the PDs as well.

Reference is made to FIGS. **39** and **40**, which are illustrations of two beams from one emitter to two respective PDs, in

accordance with an embodiment of the present invention. FIG. **39** shows how beams from one LED **106** arrive at two PDs **205** and **206** as a result of lenses **405-407**. Shown in FIG. **39** are beam **320** from LED **106** to PD **205** and beam **321** from LED **106** to PD **206**. FIG. **40** shows beams **320** and **321** inside an entire light guide frame **410** surrounded by LEDs **102-103** and PDs **202-203**.

Reference is made to FIGS. **41-43**, which are illustrations of an arrangement of components, light guides, PCB and screen in a device, in accordance with an embodiment of the present invention. FIG. **41** shows a portion of a touch screen assembly according to the present invention. Two light guides **411** and **412** are placed along two perpendicular edges of screen **802**. An array of LEDs **103** is arranged on PCB **652** behind light guide **411**.

FIG. **42** shows a view from above of a portion of the arrangement shown in FIG. **41**. FIG. **42** shows one LED **103** facing light guide **411**; PCB **652** and screen **802**. Curved inner lens surface **401** faces LED **103**.

FIG. **43** shows a side cutaway view of a portion of the arrangement shown in FIG. **41**, except that LED **103** is replaced by PD **210** encased in PD shell **211**. FIG. **43** also shows light guide **411** having inner surface **401**, PCB **652** and screen **802**. In the cross-section view shown in FIG. **43** inner surface **401** is curved along its height in order to collimate light along the height of lens **411**, i.e., perpendicular to the screen. This cross-section is through the optical axis, which is the center of PD **201**, and the curve seen is for the forward 0° field illustrated in FIGS. **36-38**. If the cross-section were done in another plane, the curvature would be different to suit the corresponding field angle.

A second option is a light guide featuring both refractive elements and reflective elements. This light guide enables utilizing light emitted from the LED at more extreme angles than lenses that use only refraction, thereby gathering more of the emitted LED light. This light guide allows for a wider pitch within a limited space in the light direction, i.e., a more extreme ratio between the pitch and the depth/length from the chip to the end of the light guide.

Reference is made to FIGS. **44** and **45**, which are simplified illustrations of a light guide, in accordance with an embodiment of the present invention. FIG. **44** shows a light guide **416**, three light emitters **107-109** and the "pitch" and "depth" mentioned above. FIG. **45** shows a compound lens embodiment, including light guide **416** and three LEDs **107-109**. Light guide **416** has three identical sections, one opposite each of the LEDs. Similar compound lenses are used for the PDs. Light guide **416** has an exceptionally wide viewing angle **419** as a result of refractive surfaces **420** and reflective surfaces **421**. Light directed forward from the emitter is not reflected; it is collimated by collimating optical surface **422**.

Thus three portions of the output light field **343** are: central, collimated portion **344**, and left and right collimated portions **345** and **341**. Two gaps **342** in output light field **343** are shown. These are caused by radii **417** joining refractive surface **420** to refractive surface **422** and to reflective surface **421**, respectively. Several methods are provided for covering gaps **342**, using either microstructures, air gaps in the light guide, or a combination thereof. The air gap solutions close gaps **342**, whereas the microstructure configurations reduce the severity of gaps **342**, but do not remove them entirely.

Reference is made to FIG. **46**, which is a simplified illustration of how microstructures reduce the problem of gaps in the light field, in the light guide of FIGS. **44** and **45**, in accordance with an embodiment of the present invention. FIG. **46** shows the effect of light-scattering micro-structures applied to outer lens surface **423**. Gaps **342** in light field **341** illustrated in FIG. **45** are now covered by scattered beams **346**.

Another method of covering gaps **342** uses an air-gap in the light guide. Two variations are provided. Reference is made to FIGS. **47-49**, which are simplified illustrations of light guides, in accordance with an embodiment of the present invention. FIG. **47** shows light guide **429** separated by air gap **432** from lens **433**. Lens **433** may be a flat transparent sheet used to provide a straight border to the touch area. Light guide **429** differs from light guide **416** mainly in its central collimating portion. In light guide **416** the forward-directed light is collimated by a single refraction at entry surface **422**, whereas in light guide **429**, this light is collimated by two refractions: at entry surface **430** and at exit surface **431**. The refraction at entry surface **430** directs the light such that when it exits surface **431**, it covers the gap in the light field, as illustrated by light field **347**.

FIG. **48** shows an alternative light guide **440** that covers gaps **432** by directing light in the left and right portions of light guide **440**, instead of the in the central portion. Light guide **440** is separated by air gap **443** from lens **444**. Lens **444** may be a flat transparent sheet used to provide a straight border to the touch area, as lens **433** in FIG. **47**. Light guide **440** differs from light guide **416** mainly in its left and right reflecting and refracting portions. In light guide **416** the wide-angle light is collimated by a refraction at entry surface **420** followed by a reflection at surface **421**, whereas in light guide **440**, one further refraction is required at exit surface **442**. The reflection at surface **441** directs the light such that when it exits surface **432**, it covers the gap in the light field, as illustrated by light field **348**.

Light guides **416**, **429** and **440** all collimate light in a first dimension, parallel to the screen surface. A curved mirror is used to collimate the light beams in the dimension incident to the screen surface. FIG. **49** shows LEDs **107-109**, light guide **416** for collimating light from these LEDs in a first direction, and curved mirror **451** for collimating these light beams in a second direction. A second light guide **452** directs these beams across screen **802**.

For some methods it is useful that the beam intensity varies linearly along the width of light field **343**. Reference is made to FIG. **50**, which is a simplified illustration of a light intensity distribution across the width of a wide light beam, in accordance with an embodiment of the present invention. FIG. **50** shows linear light intensity distribution **355** across the width of wide beam **354**. The other elements in FIG. **50** are screen **802**, LED **106** and its associated lens **407**, PDs **205** and **206**, and their associated lenses **405**, **406**. Reference is made to U.S. Publication No. 2011/0163998 A1 entitled OPTICAL TOUCH SCREEN SYSTEMS USING REFLECTED LIGHT, the contents of which are incorporated herein in their entirety by reference, which explains how a linear light intensity distribution is used to determine a touch location inside a wide beam. However, due to the reflection at the outer edges of light guides **416**, **429** and **440**, the outer sections of light field **343** are inverted, as will be explained with reference to FIG. **51**.

Reference is made to FIG. **51**, which is a simplified illustration comparing light intensity distribution across the width of an un-reflected wide light beam with that of a wide beam that has passed through the light guide of FIGS. **44** and **45**, in accordance with an embodiment of the present invention. FIG. **51** compares the light intensity distributions from a first emitter **106** with those from a second emitter **108** passing through light guide **416**. The linear distribution **356** from emitter **106** is rearranged by light guide **416** into three distri-

butions **357-359**. Distributions **358** and **359** are directionally different than their neighboring portions of distribution **357**. The microstructures discussed in reference to FIG. **46** ameliorate this problem. However, an alternative light guide avoids this problem entirely while still capturing a wide viewing angle.

Reference is made to FIGS. **52-54**, which are simplified illustrations of a light guide, in accordance with an embodiment of the present invention. FIG. **52** shows three lenses **460** of a light guide that also captures a wide viewing angle, and has the added advantages of no gaps in the light field and the light field can be easily shaped, e.g., to provide linear light intensity distributions as discussed hereinabove with reference to FIGS. **50** and **51**. Lens **460** uses refraction and reflection to capture and collimate light across a wide viewing angle. Each lens in FIG. **52** is opposite respective diode **107-109**. This lens features an upper portion **466** and a lower portion **467**. Lower portion **467** features refractive surface **463** facing the lens's respective diode and curved internally reflective surface **461** cut horizontally by a bottom horizontal plane **484**. Upper portion **462** features refractive surface **464** above the lens's respective diode and curved internally reflective surface **462** cut horizontally by a top horizontal plane **483**.

In some embodiments, refractive surface **463** is a single-curved (x-dimension) surface. In other embodiments the surface facing the diode is straight. Internally reflective surfaces **461** and **462** further collimate the light in both the x- and y-directions. When diodes **107-109** are emitters, collimated light exits lens **460** through flat exit surface **464**. When diodes **107-109** are receivers, collimated light enters lens **460** through flat exit surface **464**. By cutting reflective surfaces **461** and **462** horizontally with horizontal planes **483** and **484**, instead of vertically, the lens has a lower height, as explained above.

FIG. **53** shows a view from above of lens **460**. Diode **108** is either an LED or PD. FIG. **53** shows curved entry surface **463** and flat exit surface **464** of lens **460**. Light beams **465** are refracted at entry surface **463**.

FIG. **54** shows a cutaway view from the side of light guide **460**. FIG. **54** shows how reflective surfaces **461** and **462** collimate light beams **465** in the y and x directions. Surfaces **461** and **462** are curved in both the x and y directions to collimate the light in both these directions, and are cut horizontally by respective horizontal planes **484** and **483**. Surfaces **461** and **462** are vertically aligned mirror images of each other. This ensures that any light reflected by one of these surfaces is also reflected by the other surface. Entry surface **463** and exit surface **464** of lens **460** are also shown.

Lens **460** is an extremely fast lens suitable for applications requiring much light, yet is extremely compact. For example, in prior art systems in which a diode is placed underneath the screen, light guides for collimating light in the x-direction, i.e., parallel to the screen surface, employ a curved reflective surface that receives the light traveling downward, perpendicular to the x-direction. In prior art lenses, a double-curved reflector is cut vertically by a rear vertical plane of the light guide. The advantages of lens **460** are evident when it is compared to a prior art light guide illustrated in FIG. **55**.

Reference is made to FIG. **55**, which is a prior art illustration of a light guide. FIG. **55** shows diode **108** opposite a prior art collimating light guide **470** having a single reflector curved in two-dimensions for collimating light from LED **108**. The reflector has a height **478** which is the sum of two heights: (a) height **476** which is determined by the height of exit surface **474**. This is the height of the incoming light channel which must be maintained as the light travels through light guide **470**; and (b) height **472** of the parabola resulting from the fact that double-curved reflector **471** is intersected by backplane **481**. The magnitude of height **472** depends on the width of the pitch between neighboring LEDs and the proximity of LED **108** to light wide **470**. Namely, a wider viewing angle requires a greater parabolic height.

By contrast, the minimum height of lens **460** of FIGS. **52**, **53**, **54** and **56**, is limited only to twice the height of the incoming light channel, i.e., the sum of the heights of surfaces **463** and **464**. The parabola of FIG. **55** is rotated from the vertical plane to the horizontal plane in lens **460**. Therefore height **472** in light guide **470** is transposed into depth **482** in the horizontal plane in lens **460** as illustrated in FIG. **52**.

Moreover, because lens **460** has two double-curved reflectors it is more powerful, nearby twice as powerful, as light guide **470**. Thus, for wide viewing angles the parabolic depth required in lens **460** is substantially less than the parabolic height required in light guide **470**.

Reference is made to FIG. **56**, which is a simplified illustration showing example dimensions of lens **460** of FIGS. **52**, **53**, **54**, in accordance with an embodiment of the present invention. Lens **460** can be made less extreme with a flat entry surface and longer focal length. The distance between neighboring lenses can also be increased if needed. Unusual curves used in lens **460** may result in extreme vignetting, which can be compensated with microstructures at exit surface **464**.

Edge Sweep Detection

Reference is made to FIGS. **57** and **58**, which are simplified illustrations of a light guide arrangement for detecting touches and sweep gestures performed upon the light guide, in accordance with an embodiment of the present invention. FIG. **57** shows an optical touch screen with an LED-PD pair for detecting an object touching the left edge of a light guide frame, in accordance with an embodiment of the present invention. FIG. **57** shows the optical touch screen of FIG. **40** where, in addition to the LEDs and PDs for detecting touch locations on the screen, an additional LED-PD pair **106-206** is added for detecting an object touching the left edge of light guide frame **410**. LED **106** projects light beam **322** into the left border of light guide frame **410** where light beam **322** is captured inside a slab portion of frame **410** by total internal reflection as it travels through. At the opposite end of this border, light beam **322** is detected by light detector **206**. The upper surface of the slab is exposed to touch by an object from outside. Such a touch absorbs a portion of light beam **322** before it arrives at detector **206**, resulting in reduced detection at detector **206**. Calculating unit **711** connected to detector **206** determines that an object is touching the upper surface of the slab portion through which beam **322** passes based on this reduced light detection.

In certain embodiments more than one LED-PD pair is provided in order to detect movement of the object across the upper surface in a direction perpendicular to beam **322**. This enables the computer to determine that a sweep gesture across the border is being performed, corresponding to the sweep gesture employed by Windows 8 to open the charms bar or to toggle between different running applications. FIG. **58** shows two emitters **106**, **107** that emit beams **322**, **323**, respectively, through light guide **411**, with each beam being detected by a corresponding detector (not shown) at the opposite end of each beam, in accordance with an embodiment of the present invention. FIG. **58** shows emitters **106** and **107** that emit respective beams **322** and **323** through light guide **411**. These beams are confined inside light guide **411** by total internal reflection. Each beam is detected by a corresponding detector (not shown) at the opposite end of each beam. A sweep gesture indicated by arrow **900** across light guide **411** is

detected as a result of portions of internally reflected beams **322** and **323** being absorbed by a finger performing the gesture as the finger comes into contact with each beam. Furthermore, in certain embodiments, each border of frame **410** (in FIG. **57**) has multiple LED-PD pairs for detecting these Windows 8 edge-related sweep gestures along each edge of the screen.

Reference is made to assignee's U.S. Pat. No. 8,553,014, and co-pending U.S. patent application Ser. No. 14/016,076, both entitled OPTICAL TOUCH SCREEN USING TOTAL INTERNAL REFLECTION, which are incorporated herein in their entirety by reference, and which describe how to project light beam **322** from emitter **106** into a light guide slab and determine location of an object touching the slab's upper surface based on outputs of an opposite detector **206**.

Reduced-Component Flexible Touch Screens

Discussion now turns to embodiments of the invention wherein a touchscreen has light guides along only two edges of the screen. Reference is made to FIG. **59**, which is a simplified illustration of a touch screen having a row of emitters along the bottom edge of the screen and a row of receivers along the top edge of the screen, in accordance with an embodiment of the present invention. FIG. **59** shows screen **803**, emitter light guide **479**, detector light guide **480** and light beams **360**.

Reference is made to FIG. **60**, which is a simplified illustration of the touchscreen of FIG. **59**, in accordance with an embodiment of the present invention. FIG. **60** shows screen **803**, emitter light guide **479**, detector light guide **480** and PCB **657**.

Reference is made to FIG. **61**, which is an exploded view of the touchscreen of FIG. **59**, in accordance with an embodiment of the present invention. This view exposes LEDs **110** and PDs **207** mounted on PCB **657** underneath their respective light guides.

In another embodiment of the present invention, PCB **657** is replaced by two PCB strips. In this regard reference is made to FIG. **62**, which is a simplified illustration of a touchscreen having a row of emitters along the bottom edge of the screen mounted on a first thin strip PCB and a row of receivers among the top edge of the screen mounted on a second thin strip PCB, in accordance with an embodiment of the present invention. FIG. **62** shows a touchscreen embodiment with screen **803**, emitter light guide **479** and detector light guide **480**.

Reference is made to FIG. **63**, which is an exploded view of the touchscreen of FIG. **62**, in accordance with an embodiment of the present invention. Thus FIG. **63** shows two PCB strips **658** and **659** on which LEDs **110** and PDs **207** are mounted, respectively. As shown in FIG. **63**, light guides **479** and **480** are each made up of two parts: one above screen **803** and the other below screen **803**.

These embodiments of touchscreens having light guides along only two edges of the screen enable providing optical touch functionality on a flexible screen. In this regard reference is made to FIG. **64**, which is a simplified illustration of a foldable touchscreen, in accordance with an embodiment of the present invention. FIG. **64** shows foldable screen **803** having emitter light guide **479** along its right edge and detector light guide **480** along its left edge. Crease **804** down the middle of screen **803** indicates where the screen can be folded in half for compact storage. The unfolded screen is touch-sensitive as long as the beams projected from emitter light guide **479** arrive at detector light guide **480**. Reference is made to FIG. **65** illustrating an embodiment in which both the left and right halves of the screen have respective pairs of emitter and detector light guides **479** and **480**. In this case, even when the screen is folded along crease **804**, each half of the screen is touch sensitive. For example, when the screen of FIG. **65** is folded to roughly a 90° angle so that half of the screen lies flat on a table and the other half stands upright facing the user, in the manner of an open laptop both halves remain touch sensitive.

The determination of a touch location in these embodiments is described with reference to FIGS. **66-69**. Reference is made to FIG. **66**, which is a simplified illustration of light beams from one emitter reaching all of the detectors, in accordance with an embodiment of the present invention. FIG. **66** shows screen **803** with a row of LEDs **110** along its bottom edge and a row of PDs **207** along its top edge. Light beams **360** from one of the LEDs arrive at all of the PDs.

Reference is made to FIG. **67**, which is a simplified illustration showing which beams from FIG. **66** are blocked by an object touching the center of the screen, in accordance with an embodiment of the present invention. FIG. **67** shows what happens to beams **360** when an object **910** is placed on the screen. Thus, comparing FIGS. **67** and **66** it is evident that some of beams **360** are blocked by object **910** and their absence is detected at respective ones of PDs **207**.

Reference is made to FIG. **68**, which is a simplified illustration showing additional beams from other emitters that are not blocked by the object of FIG. **67**, in accordance with an embodiment of the present invention. FIG. **68** shows unblocked beams **360** from several of the LEDs.

Reference is made to FIG. **69**, which is a simplified illustration showing all of the beams blocked by object **910** of FIG. **67**, in accordance with an embodiment of the present invention. The area around which the intersections of these blocked beams are concentrated corresponds to the location of the object **910** on the screen. The two dimensional location of the object is thus determined. Thus, 2D coordinates of a location of a touch object correspond to the intersections of the blocked beams. Several methods for determining a touch coordinate based on a configuration of many intersecting beams have been described hereinabove with regard to avoiding ghosting. Some methods process blocked beams and others process non-blocked beams. All of these methods are also applicable to the present reduced-component embodiments.

In these embodiments the resolution of the x-coordinate, namely, the coordinate along the length of light guides **479** and **480**, is higher than the resolution of the y-coordinate. Therefore, in some embodiments of the invention the touchscreen driver software distinguishes between situations of a single touch and situations of dual touch, or multi-touch. In particular, in some embodiments, multi-touch gestures such as pinch and spread gestures are determined based only on the x-coordinates of the touches. Whereas when only one object is touching the screen the system determines both the x-coordinate and the y-coordinate of the touch object.

Furthermore, x-coordinate detection extends the entire width of the screen, i.e., to the edges of light guides **479** and **480**, whereas y-coordinate detection is limited to an inscribed rectangle within the screen in order to provide the multiple diagonal intersecting beams required in order to determine the y-coordinate.

Circular Touch Panel

Embodiments of the subject invention relate to circular touch panels. Certain circular touch panel embodiments target small touch pads and watches, and are roughly 40 mm in diameter. These embodiments support multi-touch. In certain optical touch screen implementations the channel between an LED and a PD consists of a wide beam of light, but for a round touch surface narrow ray-like beams from LED to PD are used. Thus, these embodiments are relatively small and use

tightly spaced components. This enables good light coverage even though the individual light fields are narrow.

Component Placement

Reference is made to FIGS. **70-73**, which are illustrations of alternative LED and PD layouts for a circular touch surface, in accordance with alternative embodiments of the present invention. The LEDs and PDs are positioned so that the light coverage of the touch area is maximized, i.e., the holes in the ray grid that covers the touch area are as small as possible.

Two different setup geometries are used: namely,

(i) alternating LED/PD, whereby every LED is positioned between two PDs and vice versa; and

(ii) the LEDs and PDs are positioned on separate semicircles.

(i) Alternating LED/PD

FIG. **70** shows an arrangement of alternating LEDs and PDs with an odd number of LEDs. In this case, each LED is diametrically mirrored by a PD. This kind of radial symmetry generates a large circle in the center of the touch area, mimicking a spoked wheel.

Within this circle, there is a lack of positional accuracy. When blocking one or more rays on one side of the center, there will always be another position diametrically opposite where the same rays can be blocked, thus generating the same signals. Therefore, within this circle it is not possible to determine on which side of the center a touch is located.

FIG. **71** shows an arrangement of alternating LEDs and PDs with an even number of LEDs. In this case, each LED is diametrically mirrored by another LED. This kind of radial symmetry generates a circular hole in the ray pattern at the center of the touch area. No touch information can be generated within this circle. However, it is noted that the problematic circle is smaller in this case.

(ii) LEDs and PDs Positioned on Separate Semicircles

In an embodiment of the present invention, breaking the radial symmetry associated with alternating components is achieved by splitting the circle in half and placing all of the LEDs on one side and the PDs on the other side, where the LEDs and PDs are evenly distributed. FIG. **72** shows this configuration. The PDs are arranged along the bottom semicircle and the LEDs are arranged along the upper semi-circle. Having the same number of LEDs and PDs provides a combination of the two previous layouts. There is still a central area with poor positional accuracy. The result is similar for an odd number of LEDs and PDs as each LED is now always mirrored by a PD. This setup still has a left-right symmetry associated with it. The ray pattern is improved by eliminating this symmetry. This is done, inter alia, by slightly altering the LED pitch and introducing an extra spacing of half a pitch between every third LED. This also decreases the number of LEDs. This arrangement of LEDs and PDs is illustrated in FIGS. **75** and **76**. The resulting pattern of detection beams is shown in FIGS. **73** and **77**.

Light Guide Design

Reference is made to FIG. **74**, which is an illustration of a light guide for a circular touch surface, in accordance with an embodiment of the present invention. The left pane in FIG. **74** is a cross-section of the light guide. The many-to-many mapping of LEDs to PDs requires a large angular spread of light, which is provided by the LEDs and PDs. A small focusing effect in height is introduced in the folding mirror closest to the components, as illustrated by the arc along the bottom right corner of the cross-section shown in the left pane in FIG. **74**. Other than that, the plastic light guide serves as a redirecting component to get the light across the touch area with an arrangement of mirror surfaces using total internal reflection. The curved mirror is slightly defocussed, roughly filling its corresponding diode. No draft angles are present in embodiments using a milled light guide. A consequence of the straight bezel is that the unit works when fully submerged in water, provided that it is watertight. The cross section shown in the left pane of FIG. **74** is rotated 360° to create a circularly symmetric light guide. The bezel height is 1 mm and the touch area diameter is 40 mm.

Reference is made to FIG. **75**, which is an illustration of a PCB layout for a circular touch surface, in accordance with an embodiment of the present invention. FIG. **75** shows different numbers of LEDs and PDs; namely, 11 LEDs IR**1**-IR**11** along the upper half of PCB **661**, and 12 PDs PD**1**-PD**12** along the bottom half of PCB **661**. Whereas the PDs are evenly spaced, with an angular displacement of 15° between each detector and its neighbor, the LEDs are divided into four groups with an angular displacement of 14° within each group and 21° (1.5*14°) between the groups.

In the interior of PCB **661** a plurality of electronic components is provided for the proper function of the touch sensitive surface, inter alia, controller **715**, which selectively activates and deactivates the LEDs and PDs.

Reference is made to FIG. **76**, which is an illustration of light beams emitted by one LED detected by a plurality of PDs surrounding a circular touch surface, in accordance with an embodiment of the present invention. FIG. **76** shows a range of detected beams **332** emitted by LED IR**1**. As explained above, tables measuring detected intensities of non-blocked beams are prepared in order to examine which beams are not sufficiently detectable and in order to determine a threshold value, e.g., half of the expected intensity of the non-blocked beam, for the usable beams. Thus, in practice, not all beams **332** are used to detect touches by the system. For example, the IR**1**-PD**12** beam is not used as it is detected even when the entire circular input surface is covered by an opaque object.

Reference is made to FIG. **77**, which is an illustration of a network of intersecting light beams used in a circular touch surface, in accordance with an embodiment of the present invention. FIG. **77** shows all of the used beams encircled by light guide **424** in a circular touch system according to the present invention.

Reference is made to FIG. **78**, which is a simplified illustration of a circular touch surface sensor, in accordance with an embodiment of the present invention. FIG. **78** shows a 3D model of a circular touch panel according to the present invention. A touch plate **810** is surrounded by a light guide **424**. The light beams **332**, shown in FIGS. **76** and **77**, are projected through light guide **424**. Also shown in FIG. **78** are top and bottom covers **811** and **812** and a connecting wire **912** for a haptic vibrator explained below.

Reference is made to FIG. **79**, which is an illustration of the components used to assemble a circular touch surface, in accordance with an embodiment of the present invention. FIG. **79** shows the main components in an exemplary circular touch sensor according to the present invention, namely, front cover **811**, back cover **812**, touch plate **810**, light guide **424**, PCB **661**, screws **911**, haptic vibrator **913** and its cable **912**.

Reference is made to FIG. **80**, which is an exploded view of the circular touch surface of FIG. **78**, in accordance with an embodiment of the present invention. Front and back covers **811**, **812** encase touch plate **810**, light guide **424** and PCB **661**. Also shown are screws **911**, haptic vibrator **913** and associated cable **912** that connects the device to a host system. Haptic vibrator **913** provides tactile sensory feedback through touch plate **810** in response to touch inputs detected thereon.

Reference is made to FIG. **81**, which is a cutaway view of the circular touch surface of FIG. **78**, in accordance with an embodiment of the present invention. Like reference numerals in FIGS. **80** and **81** indicate the same elements. The upper rim of light guide **424** extends above touch plate **810** forming a bezel.

Reference is made to FIG. **82**, which is a simplified illustration of a light guide for the circular touch surface of FIG. **78**, in accordance with an embodiment of the present invention. FIG. **82** shows light guide **424** with two reflective surfaces for redirecting the light beams. A light shield **421** along the inner perimeter of circular light guide **424** prevents stray light from above from hitting the light detectors.

Reference is made to FIGS. **83** and **84**, which illustrations of paths of light beams used in a circular touch surface, in accordance with an embodiment of the present invention. FIG. **83** shows the reflective properties of light guide **424**. LED **110** and PD **220** are shown facing outward of circular light guide **424**. Light beam **333** from LED **110** is projected outward into light guide **424**. Two reflective facets redirect beam **333** over and across touch plate **810**. Similar reflective facets at the opposite edge of plate **810** redirect beam **333** onto PD **220**. Light guide **424** is optimized to spread the light such that each LED has detectable beams arriving at all, or at least at many, of the PDs.

FIG. **84** shows beams **332** from LED **111**, at the center of the arc of emitters, projected onto all of the PDs. In FIG. **84**, the upper half of the circular touch area is lined with 12 PDs, and the lower half of the circular touch area is lined with 11 LEDs. The multi-tiered arrangement of LEDs, whereby groups of LEDs have a different angular displacement than neighboring LEDs within a group is described above and illustrated in FIGS. **75** and **76**.

In the foregoing specification, the invention has been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made to the specific exemplary embodiments without departing from the broader spirit and scope of the invention. Accordingly, the specification and drawings are to be regarded in an illustrative rather than a restrictive sense.

The invention claimed is:

1. A lens for placement opposite a diode in an optical touch sensor, comprising:

an upper portion comprising:

an upper refractive surface located nearer to the diode; and

an upper reflector located further from the diode, the upper reflector being curved in two dimensions and cut horizontally by a top horizontal plane of the lens; and

a lower portion, coplanar with the diode, comprising:

a lower refractive surface located nearer to the diode; and

a lower reflector located further from the diode, the lower reflector being curved in the two dimensions and cut horizontally by a bottom horizontal plane of the lens,

wherein said upper and said lower reflector are symmetrical and vertically aligned, and

wherein non-collimated light reflected by said lower reflector onto said upper reflector is partially collimated in the two dimensions by said lower reflector and further collimated in the two dimensions by said upper reflector.

2. The lens of claim **1**, wherein the height of the lens between the top and bottom horizontal planes is less than the height required for a curved reflector intersected by a rear vertical backplane of the lens to partially collimate and further collimate the non-collimated light.

3. The lens of claim **1**, wherein said upper and lower refractive surfaces are not curved.

4. The lens of claim **1**, wherein said lower refractive surface is a single-curved surface and said upper refractive surface is not curved.

5. A method for calculating multiple touch locations on a screen comprising:

activating a plurality of emitters and detectors around the perimeter of a screen, wherein each emitter-detector pair corresponds to a light beam crossing the screen, from among a plurality of such light beams, and wherein some of the light beams are blocked by one or more objects touching the screen;

providing a look-up table listing, for each light beam from the plurality of light beams, other light beams from the plurality of light beams, that intersect that light beam, and their respective points of intersection;

(a) identifying a first blocked light beam;

(b) accessing the look-up table to identify a second blocked light beam that intersects the first blocked beam;

(c) accessing the look-up table to identify intersection points of other blocked light beams that neighbor the intersection point of the thus-identified first and second blocked beams;

(d) repeating operations (b) and (c) until all neighboring intersections points of blocked beams have been identified, and group the thus-identified neighboring intersections as a single touch point; and

(e) repeating operations (a)-(d) for remaining blocked light beams that were not yet grouped at operation (d).

6. A circular touch sensor comprising:

a housing;

a surface mounted in said housing, comprising a circular portion exposed to receive touch input;

a plurality of light detectors mounted in said housing along a semicircular contour corresponding to a half of said circular portion, wherein an angular pitch between neighboring detectors is constant;

a plurality of light emitters mounted in said housing along an opposite semicircular contour corresponding to the opposite portion of said circular portion, and arranged in groups such that an angular pitch between neighboring emitters within each group is θ, and such that an angular pitch between nearest emitters in different groups is $\theta+a$, where a is positive; and

a processor connected to said emitters and to said detectors, for synchronously co-activating emitter-detector pairs, and configured to calculate a two-dimensional location of an object touching said circular portion, based on outputs of said detectors.

7. The circular touch sensor of claim **6** wherein $a=\theta/2$.

8. The circular touch sensor of claim **6** further comprising a lens surrounding said circular portion for directing light from said emitters to said detectors across said circular portion.

9. A circular touch sensor comprising:

a housing;

a surface mounted in said housing comprising a circular portion exposed to receive touch input;

a plurality of light emitters mounted in said housing along a semicircular contour corresponding to half of said circular portion, wherein an angular pitch between neighboring emitters is constant;

a plurality of light detectors mounted in said housing along an opposite semicircular contour corresponding to the

opposite half of said circular portion, and arranged in groups such that an angular pitch between neighboring detectors within each group is θ, and such that an angular pitch between nearest detectors in different groups is θ+a, where a is positive; and

a processor connected to said emitters and to said detectors, for synchronously co-activating emitter-detector pairs, and configured to calculate a two-dimensional location of an object touching said circular portion, based on outputs of said detectors.

10. The circular touch sensor of claim **9** wherein a=θ/2.

11. The circular touch sensor of claim **9** further comprising a lens surrounding said circular portion, for directing light from said emitters to said detectors across said circular portion.

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