US010502391B2

(12) **United States Patent** (10) **Patent No.: US 10,502,391 B2**
Joergensen (45) **Date of Patent: Dec. 10, 2019**

(54) **LIGHT COLLECTOR WITH A PLURALITY OF LENSLETS PACKED IN AN OPTIMIZED DENSE CIRCULAR PATTERN**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 438 days.

(21) Appl. No.: **14/561,180**

(22) Filed: **Dec. 4, 2014**

(51) **Int. Cl.**
F21V 5/00 (2018.01)
F21W 131/406 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC *F21V 5/004* (2013.01); *F21V 5/007* (2013.01); *F21W 2131/406* (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC F21S 8/003; F21V 5/004; F21V 5/045; F21V 5/048; F21V 5/007; F21V 7/04;
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,309,277 A * 5/1994 Deck H01S 5/4025
250/205
5,402,326 A 3/1995 Belliveau
(Continued)

FOREIGN PATENT DOCUMENTS

CA 2100181 A1 1/1994
CN 201680227 U 12/2010
(Continued)

OTHER PUBLICATIONS

Search Report and Written Opinion for corresponding Application No. PA 2013 70745, dated Jul. 21, 2014, 6 pages.
(Continued)

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(57) **ABSTRACT**

The present invention relates to a light collector adapted to collect light from a plurality of light sources and where the light collector comprises a plurality of lenslets collecting light from the light sources and convert the light into a plurality of light beams propagating along an optical axis. The lenslets are arranged in a dense pattern, where at least 12 outermost adjacent lenslets is located along an outer circular boundary having the same radial distance to a center of the light collector. The dense pattern has been obtained by optimizing a packaging density defined by a ratio of a sum of areas of circular cross sections of the lenslets and an area of the outer circular boundary and that the packaging density is at least 0.79.

18 Claims, 25 Drawing Sheets
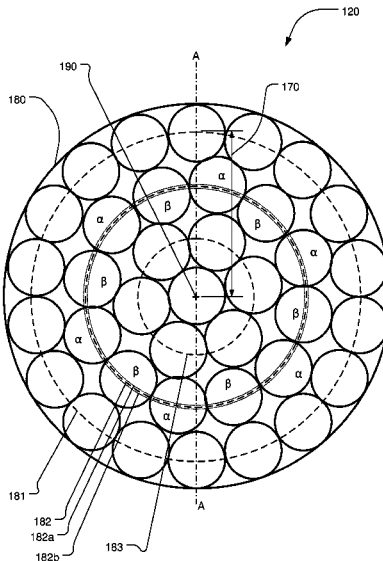
(51) **Int. Cl.**
    F21Y 105/10   (2016.01)
    F21Y 115/10   (2016.01)
    F21Y 105/18   (2016.01)

(52) **U.S. Cl.**
    CPC *F21Y 2105/10* (2016.08); *F21Y 2105/18*
           (2016.08); *F21Y 2115/10* (2016.08)

(58) **Field of Classification Search**
    CPC F21Y 101/00; G02B 19/0014; G02B 3/00;
                               G03B 21/00
    See application file for complete search history.

(56)   **References Cited**

U.S. PATENT DOCUMENTS

5,690,417 A *	11/1997	Polidor	G02B 21/084
			359/387
5,808,657 A	9/1998	Kurtz et al.	
5,850,126 A	12/1998	Kanbar	
6,227,669 B1	5/2001	Tiao et al.	
6,402,347 B1	6/2002	Maas et al.	
6,443,594 B1	9/2002	Marshall et al.	
6,601,973 B2	8/2003	Rasmussen et al.	
6,687,063 B1	2/2004	Rasmussen et al.	
7,226,185 B2	6/2007	Dolgin et al.	
7,715,703 B2 *	5/2010	Utagawa	G03B 13/36
			348/345
9,441,805 B2	9/2016	Godbillon	
2005/0174768 A1 *	8/2005	Conner	G02B 27/1053
			362/235
2005/0180690 A1 *	8/2005	Sugiyama	B29C 33/3842
			385/33
2006/0078015 A1	4/2006	Franck	
2006/0139918 A1	6/2006	Dolgin et al.	
2007/0046898 A1	3/2007	Conner	
2007/0051964 A1 *	3/2007	Owen	F21K 9/00
			257/98
2008/0084693 A1	4/2008	Shimada et al.	
2009/0122548 A1	5/2009	Dalsgaard	
2009/0316417 A1 *	12/2009	Chari	G02B 6/0051
			362/326
2010/0073783 A1	3/2010	Sun	
2011/0063836 A1 *	3/2011	Salm	F21V 5/007
			362/235
2012/0121244 A1	5/2012	Stavely	
2012/0127710 A1	5/2012	Jurik et al.	
2012/0319616 A1	12/2012	Quilici et al.	
2013/0271994 A1	10/2013	Hsu et al.	
2013/0343035 A1	12/2013	Sakai et al.	
2014/0133142 A1	5/2014	Joergensen	
2014/0133143 A1	5/2014	Ebner	
2015/0211708 A1	7/2015	Stavely et al.	
2015/0285483 A1	10/2015	Kjaer et al.	

FOREIGN PATENT DOCUMENTS

CN	101988650 A	3/2011	
CN	102695915 A	9/2012	
CN	102803834 A	11/2012	
CN	103154601 A	6/2013	
EP	1710493 A2	10/2006	
EP	2309296 A1	4/2011	
JP	2005347279 A	12/2005	
JP	2006269182 A1	10/2006	
KR	200446413	10/2009	
KR	101302736 B1	9/2013	
WO	0102771 A1	1/2001	
WO	0198706 A1	12/2001	
WO	03025458 A1	3/2003	
WO	2006023180 A1	3/2006	
WO	2011076213 A1	6/2011	
WO	2011076219 A1	6/2011	
WO	2011100973 A1	8/2011	
WO	2011116769 A1	9/2011	
WO	2012067956 A2	5/2012	
WO	2012167800 A1	12/2012	
WO	2013060329 A1	5/2013	

OTHER PUBLICATIONS

Search Report and Written Opinion for corresponding Application No. PA 2013 70746, dated Jul. 22, 2014, 6 pages.

Search Report and Written Opinion for corresponding Application No. PA 2013 70747, dated Jul. 21, 2014, 8 pages.

Lubachevsky et al., "Curved Hexagonal Packings of Equal Disks in a Circle", Discrete & Computational Geometry, 18, 1997, pp. 179-194.

Lubachevsky et al., "Geometric Properties of Random Disk Packings", Journal of Statistical Physics, vol. 60, Nos. 5/6, 1990, pp. 561-583.

Lubachevsky et al., "Dense Packings of 3k(k+1)+1 Equal Disks in a Circle for k=1, 2, 3, 4, and 5", Springer Lecture Notes in Computer Science 959, 1996, 18 pages.

Graham et al., "Dense Packings of Equal Disks in an Equilateral Triangle: From 22 to 34 and Beyond", The Electronic Journal of Combinatorics, 2, 1995, 39 pages.

Lubachevsky, "How to Simulate Billiards and Similar Systems", J. Computational Physics, 94, 1991, 29 pages.

Innobiz document related to KR 20-0446413, dated Oct. 28, 2009, 2 pages.

European Office Action for corresponding Application No. 14 196 447.8, dated Nov. 9, 2016, 6 pages.

U.S. Office Action for U.S. Appl. No. 14/561,178, dated Feb. 22, 2017, 13 pages.

U.S. Office Action for U.S. Appl. No. 14/562,336, dated Apr. 11, 2017, 27 pages.
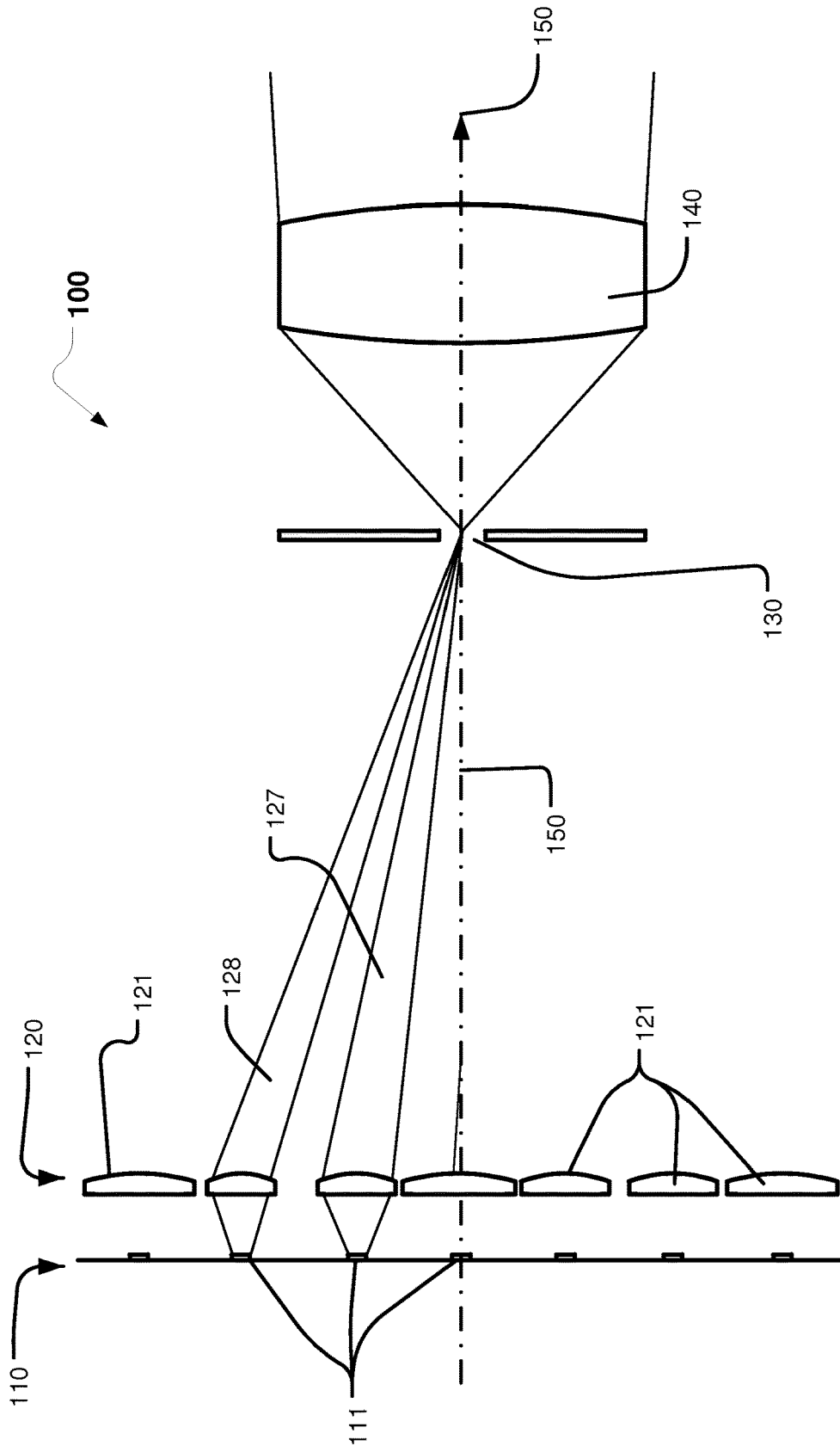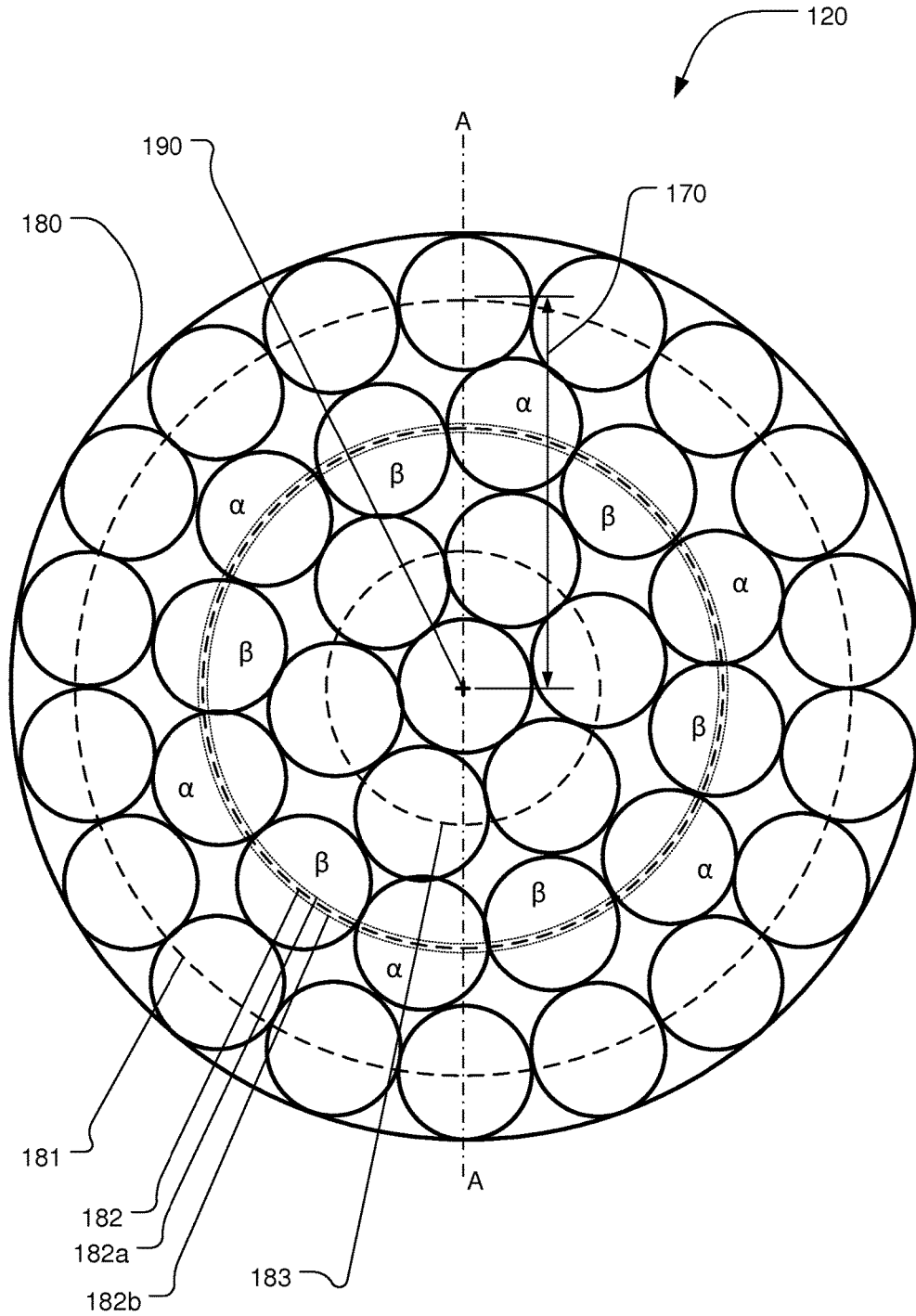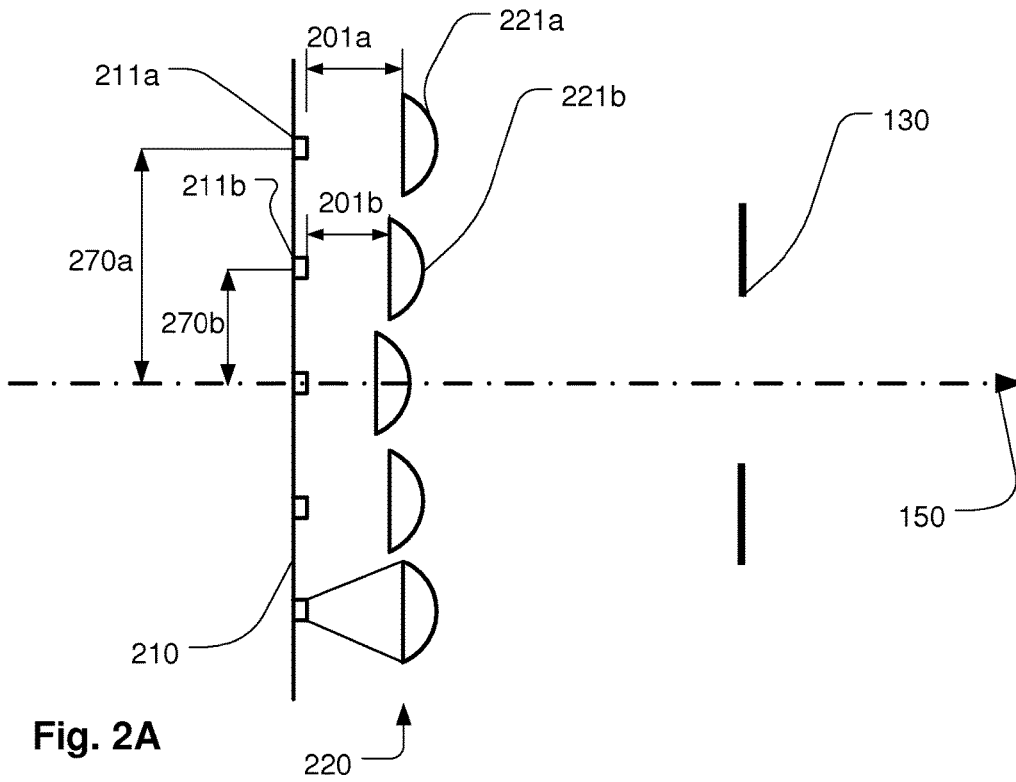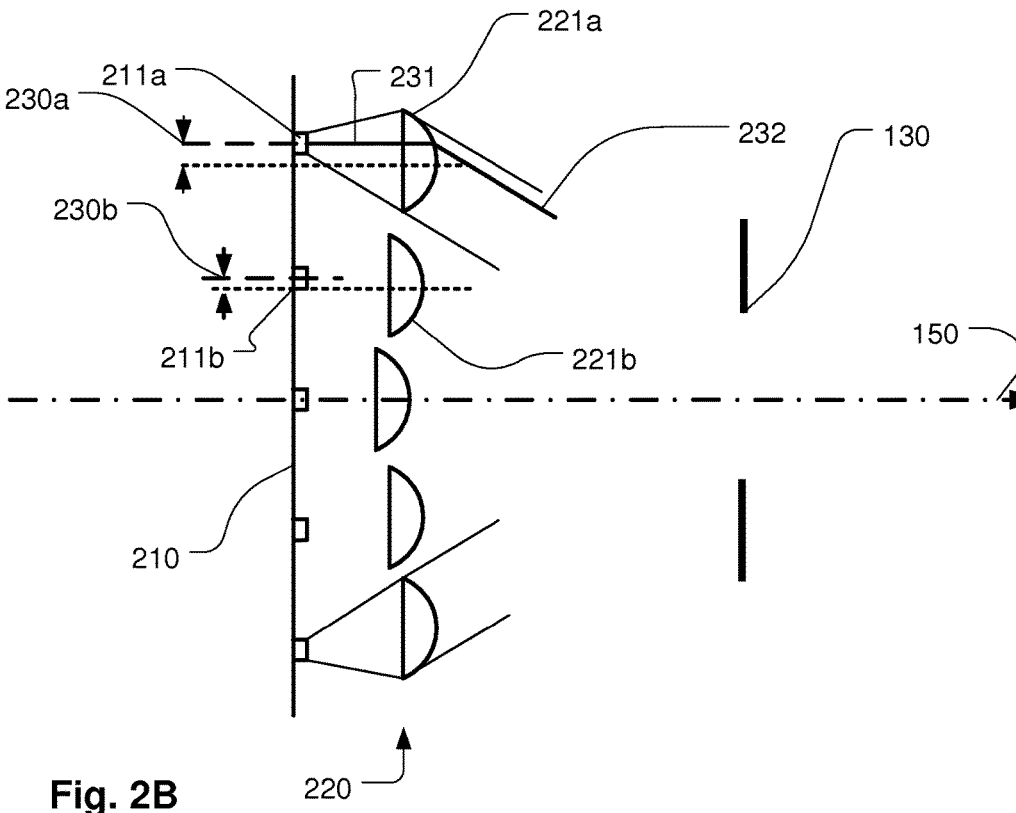
* cited by examiner

Fig. 1A

Fig. 1B

Fig. 2A

Fig. 2B

Fig. 2C

Fig. 3A

Fig. 3B
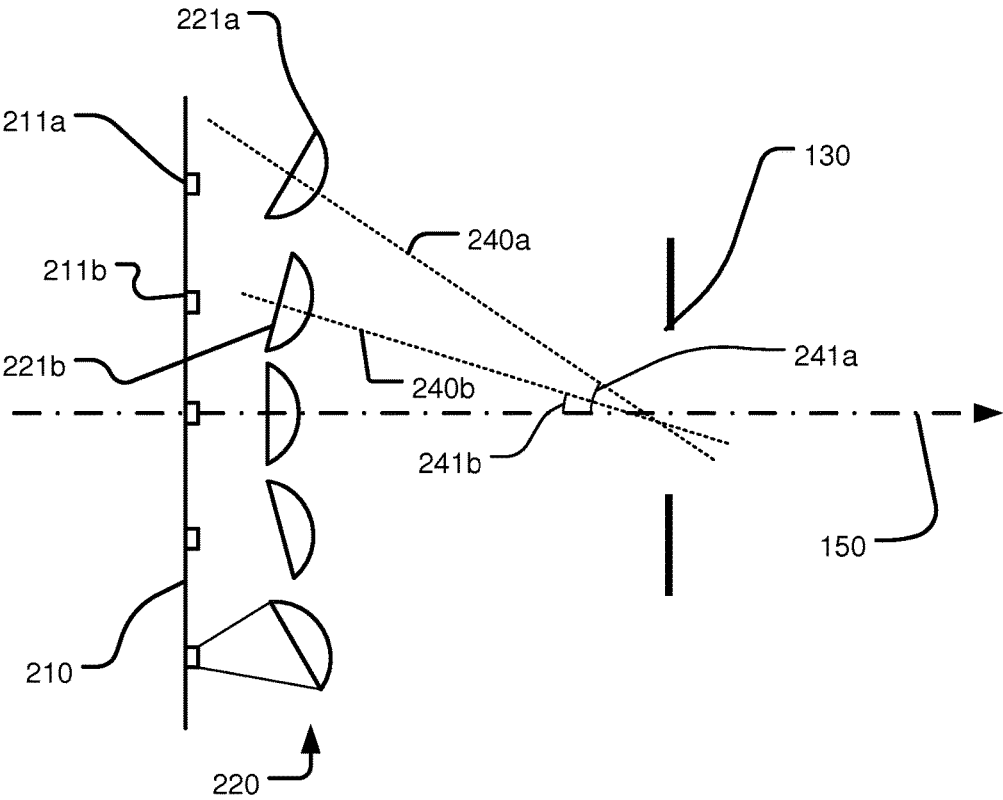
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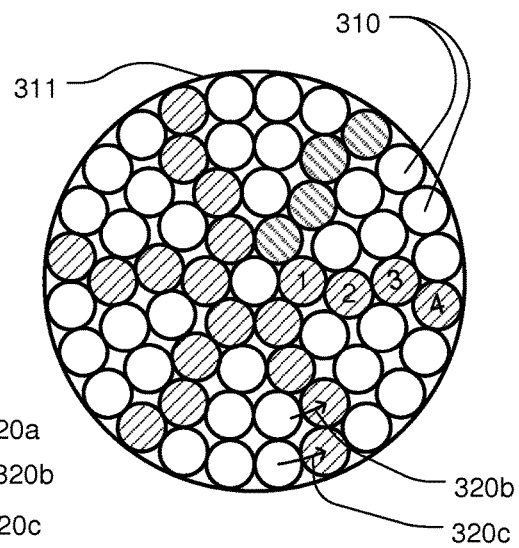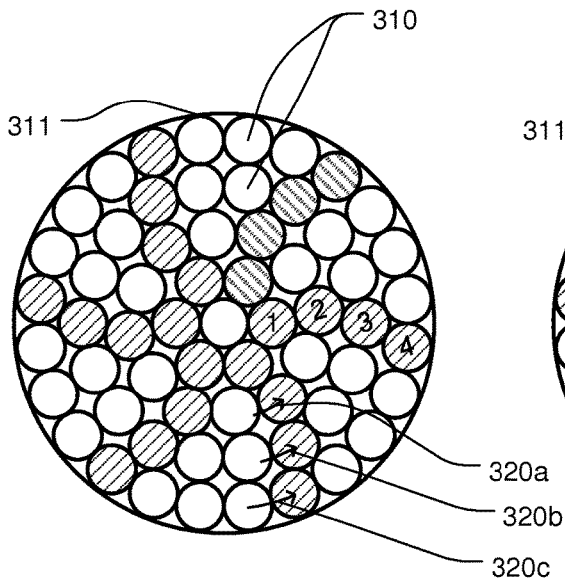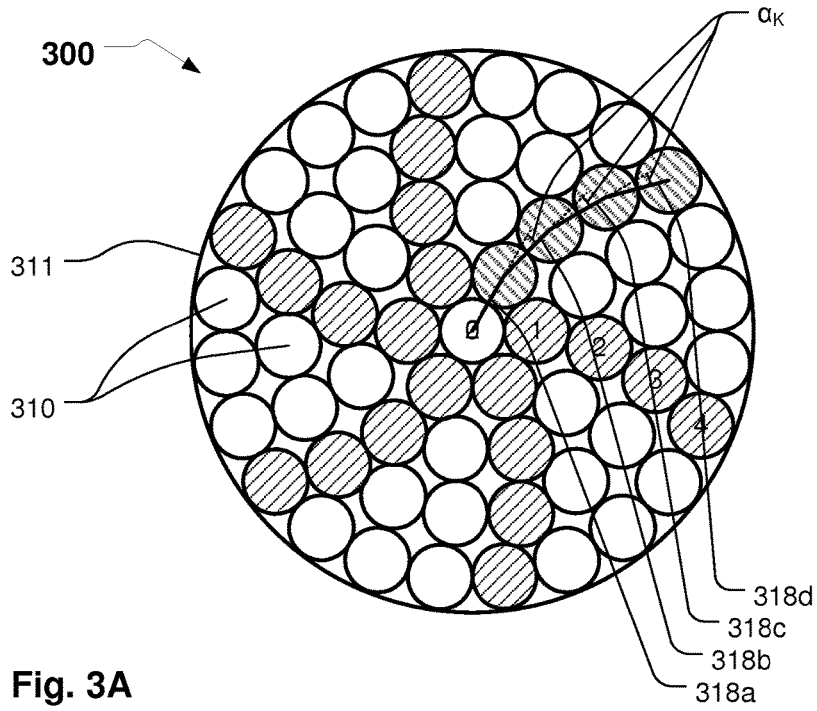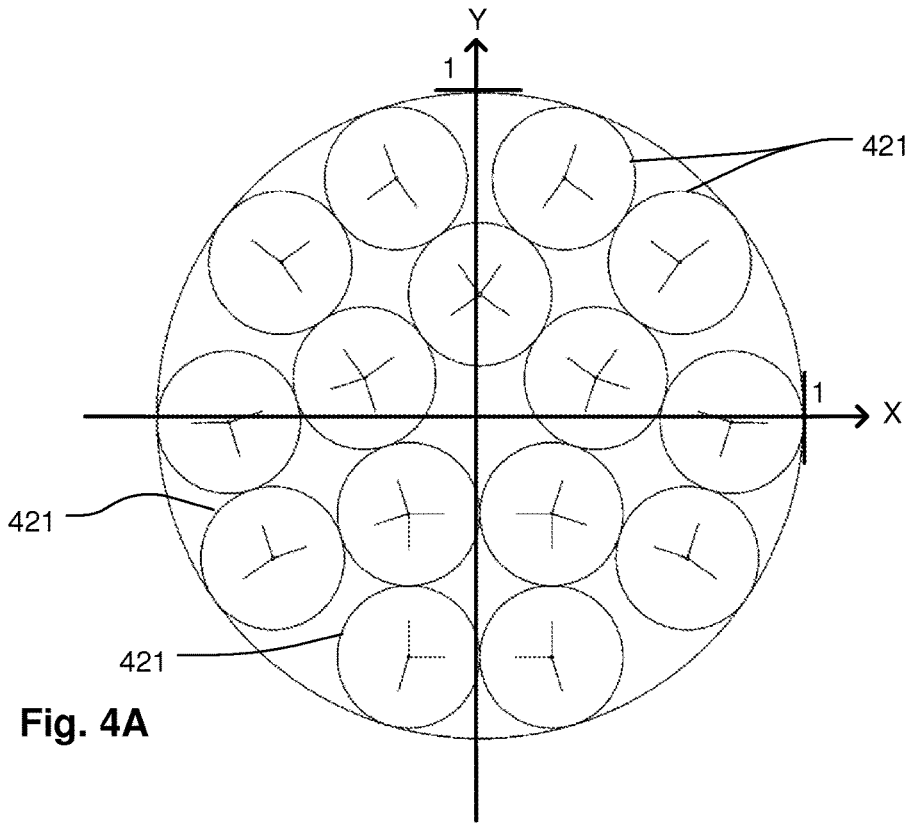
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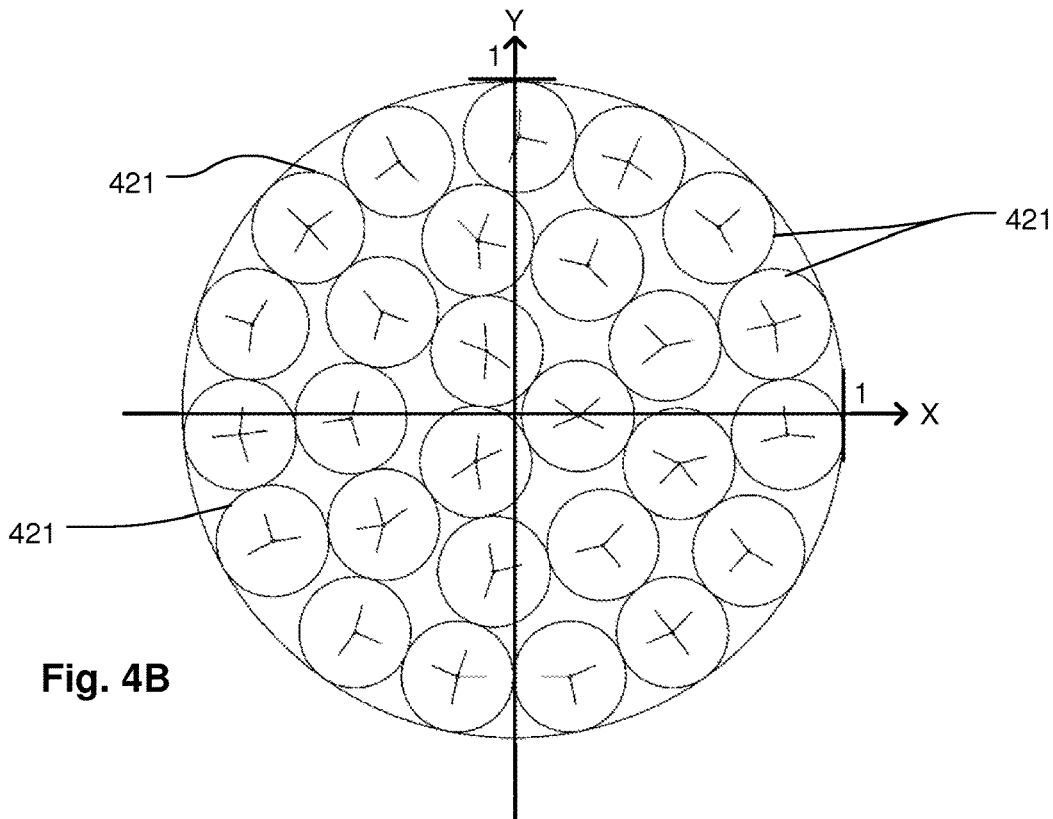
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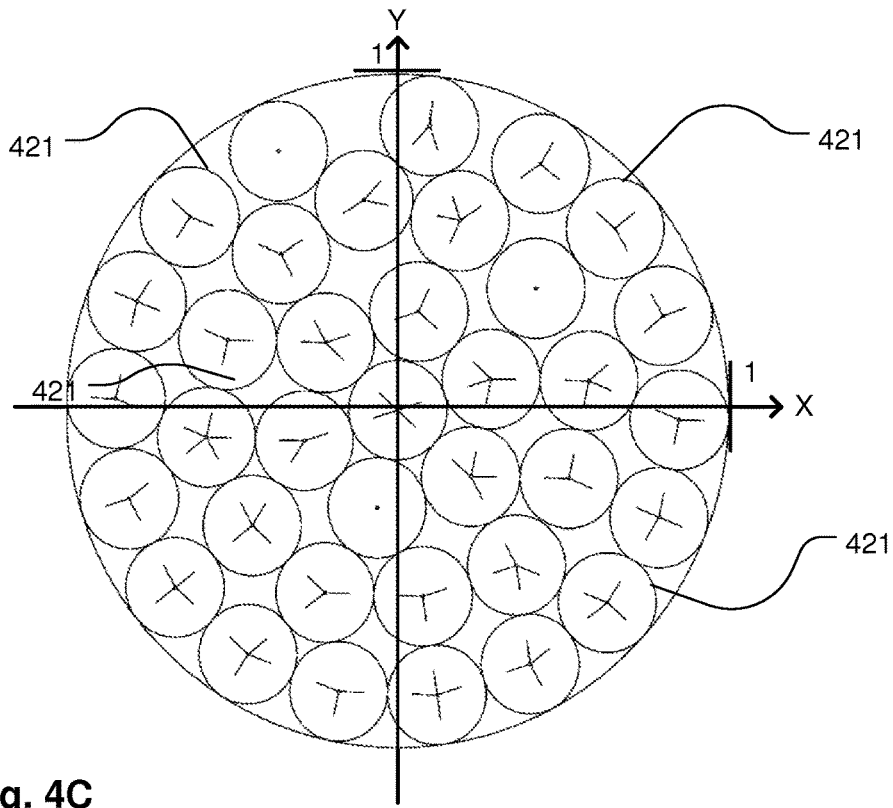
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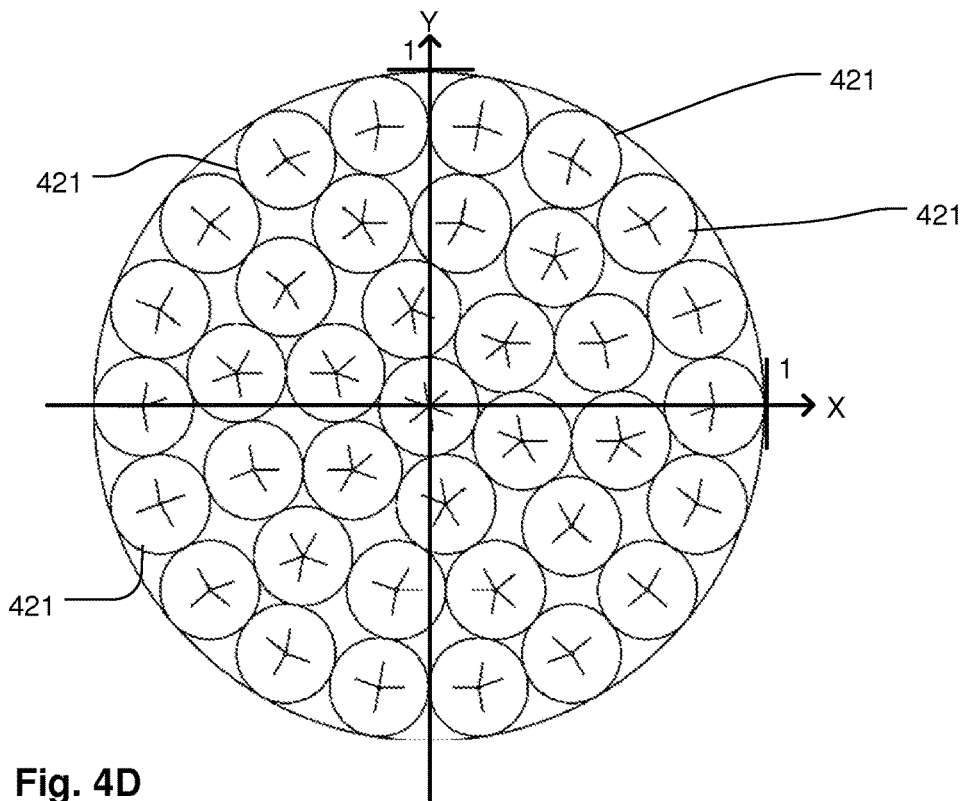
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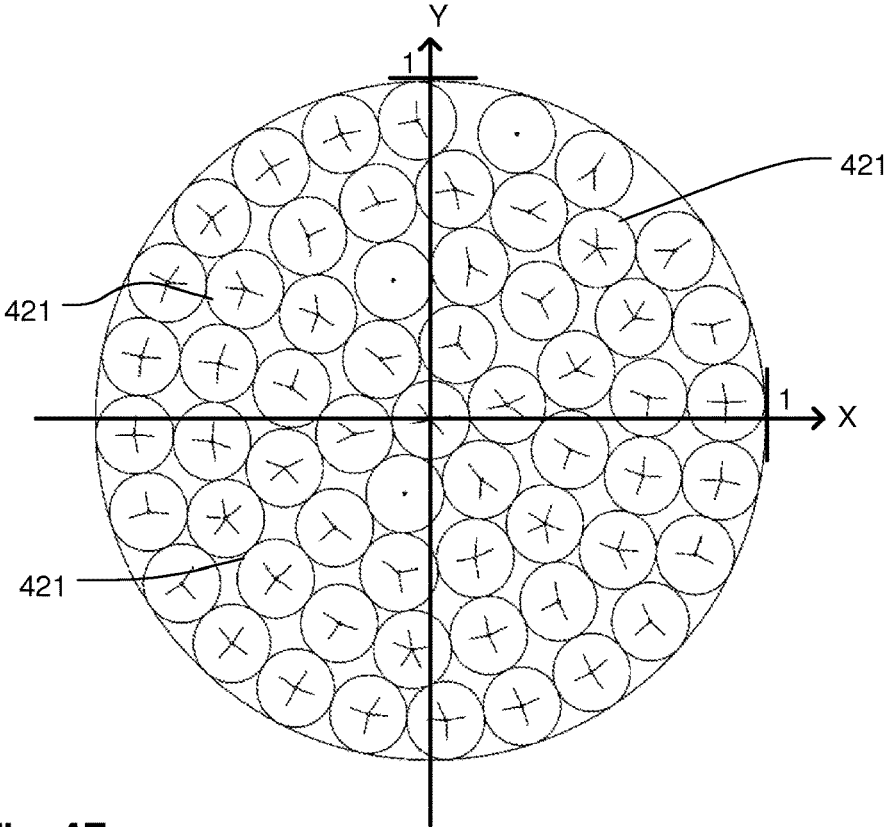
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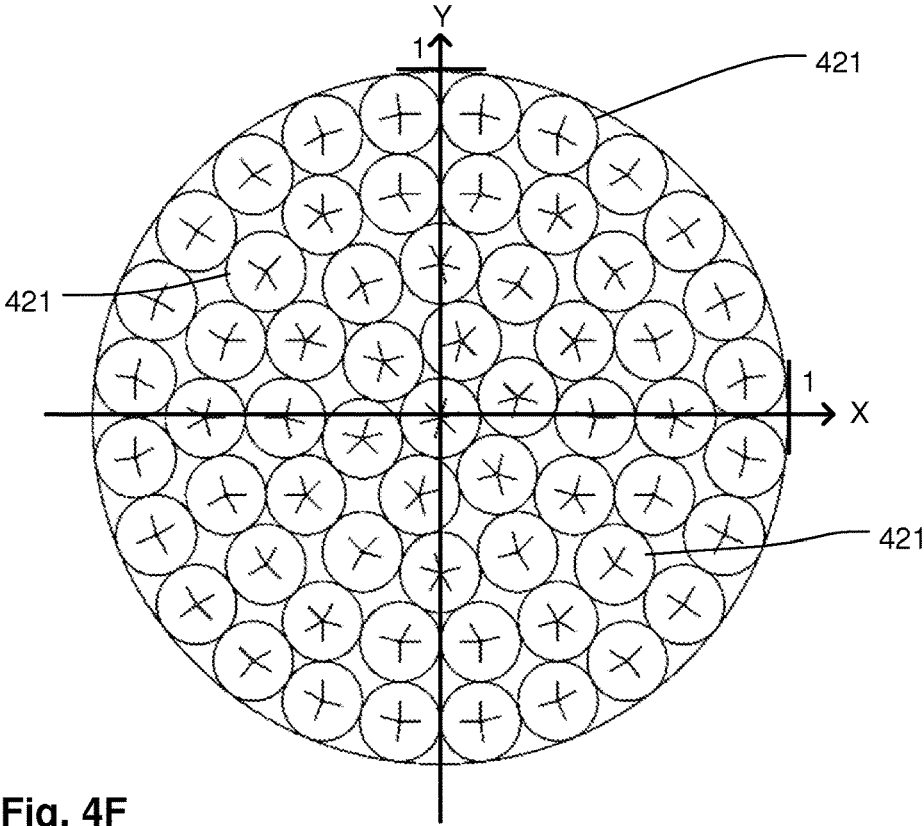
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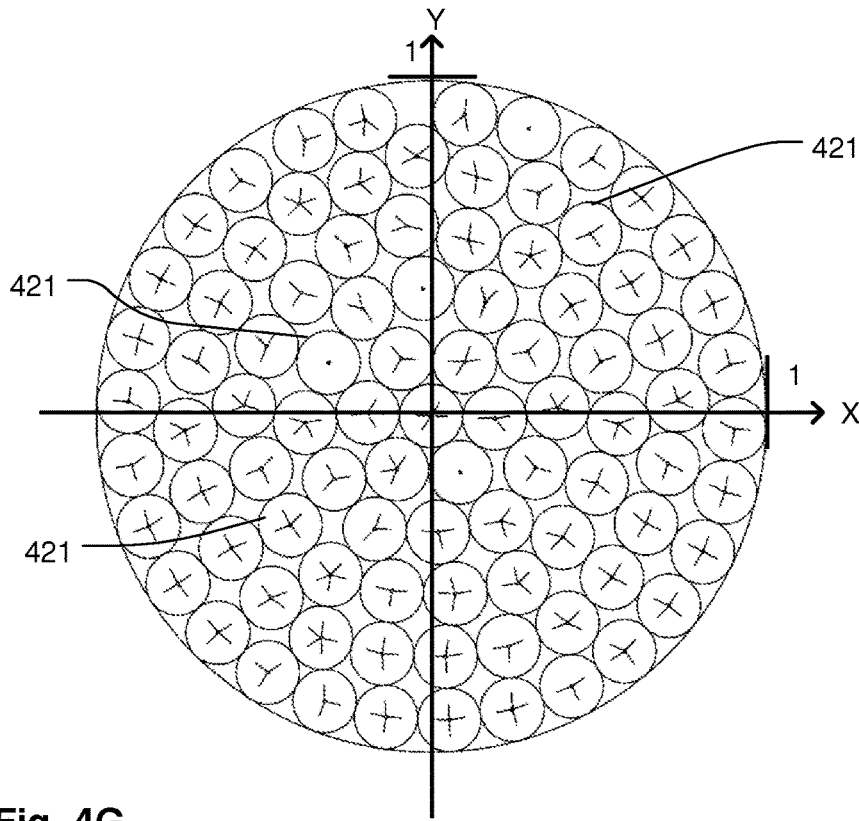
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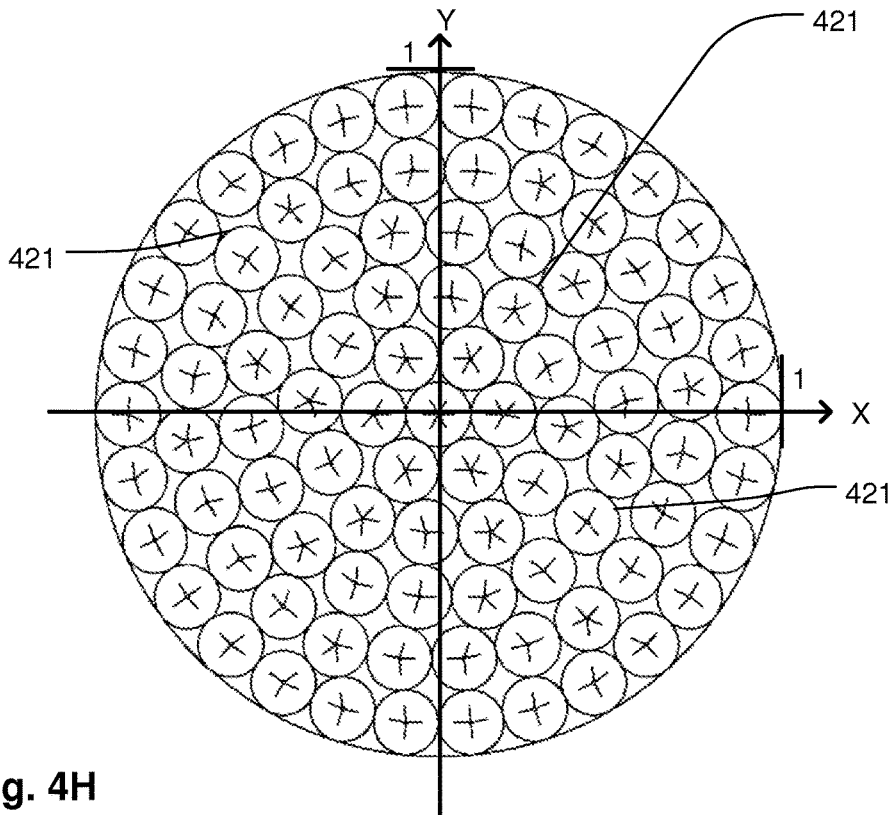
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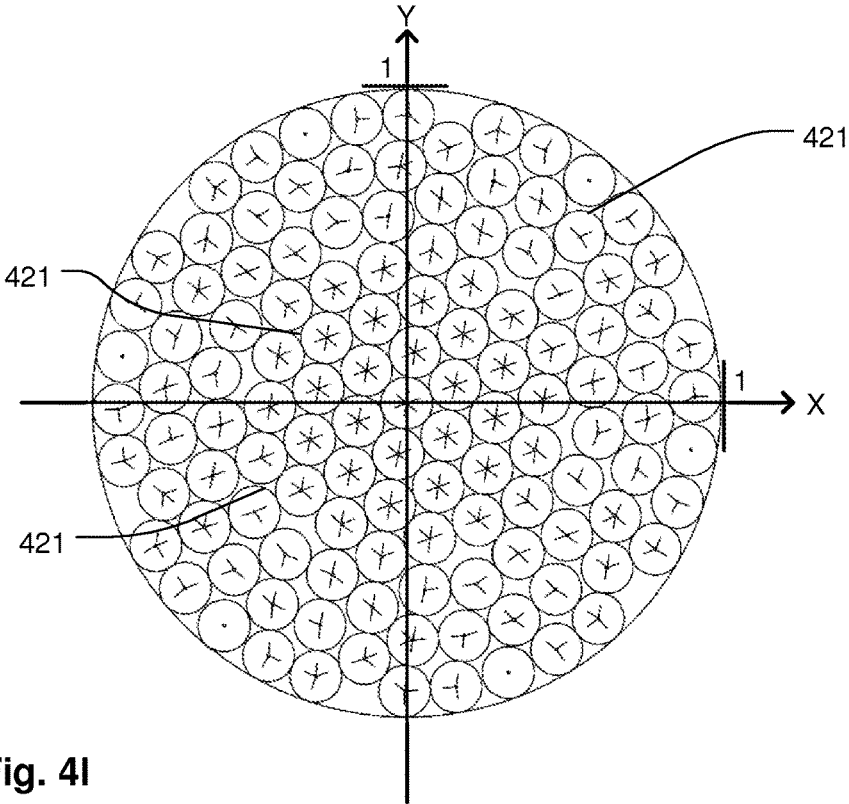
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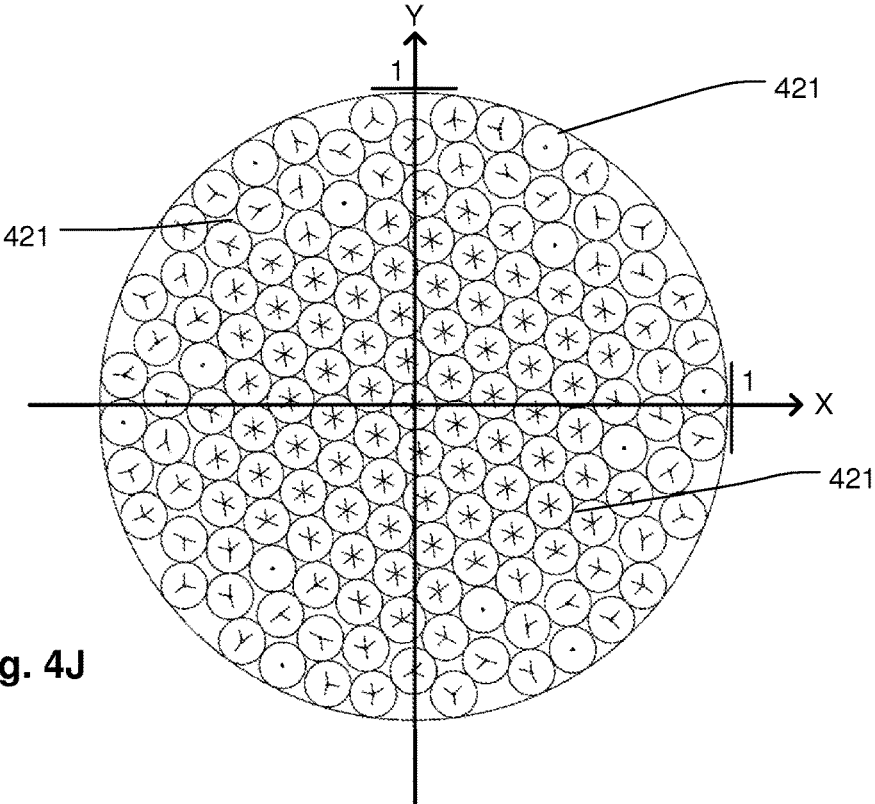
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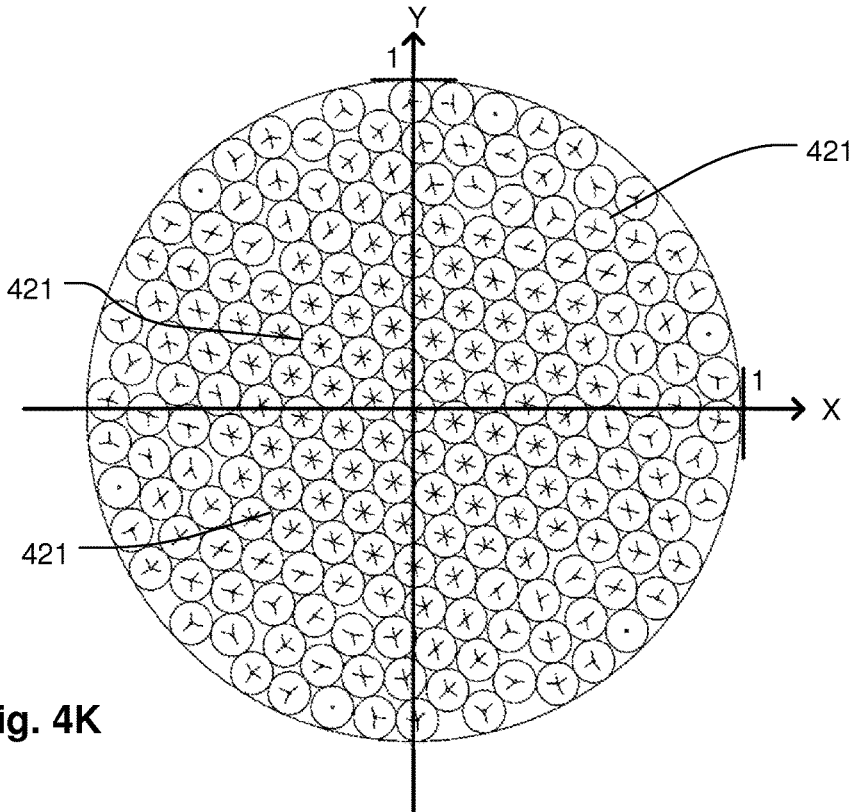
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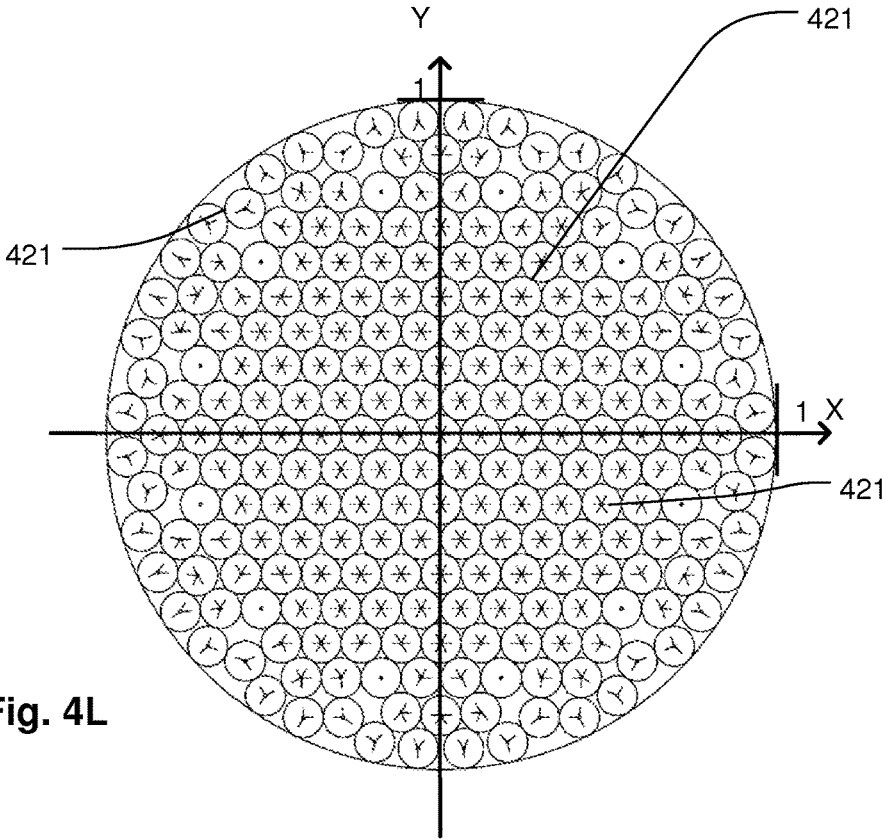
Fig. 4L

Fig. 5A

Fig. 5B

Fig. 5C

520

521c

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551b

521b

150

521a

559

557c

557b

553b

553b

555b

557a

557b

561

Fig. 5D

520

521c

150

521b

521a

Fig. 5E

Fig. 6A

Fig. 6B

Fig. 6C

Fig. 7A

Fig. 7B

Fig. 7C

Fig. 7D

820

821a   821b   821c

Fig. 8A

820   821a   821c
              821b

Fig. 8B

820   821b   821c
821a

Fig. 8C

820   821b   821c
821a

Fig. 8D

821a   821b   821c   820

B'A'   A'B'
C'   C'

Fig. 8E

861

821a   821b   821c   820

Fig. 8F

821a   821b   821c   820

Fig. 8G

821a   821b   821c   820

859

Fig. 8H

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Fig. 9A

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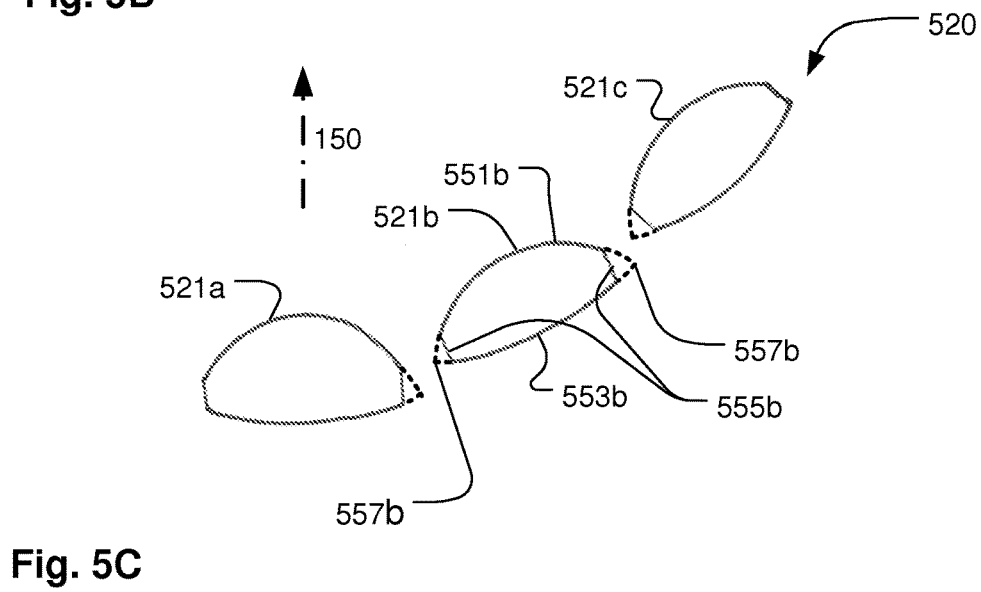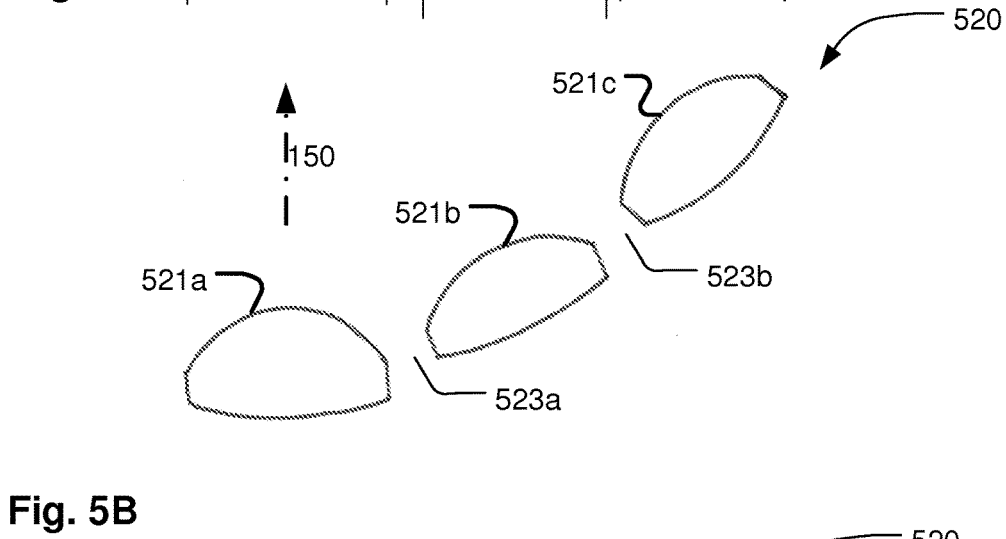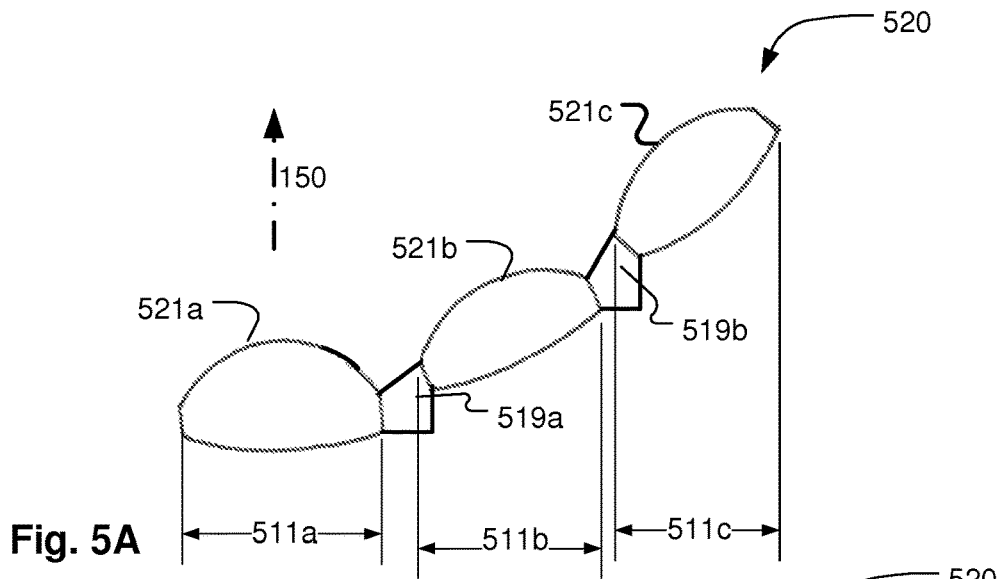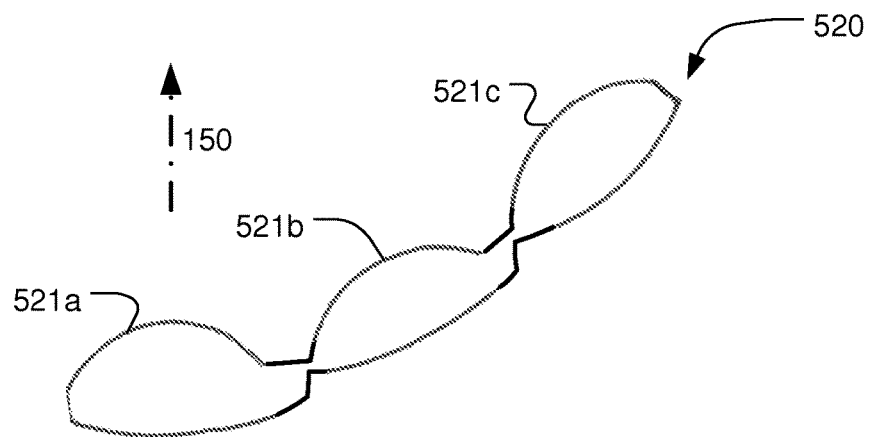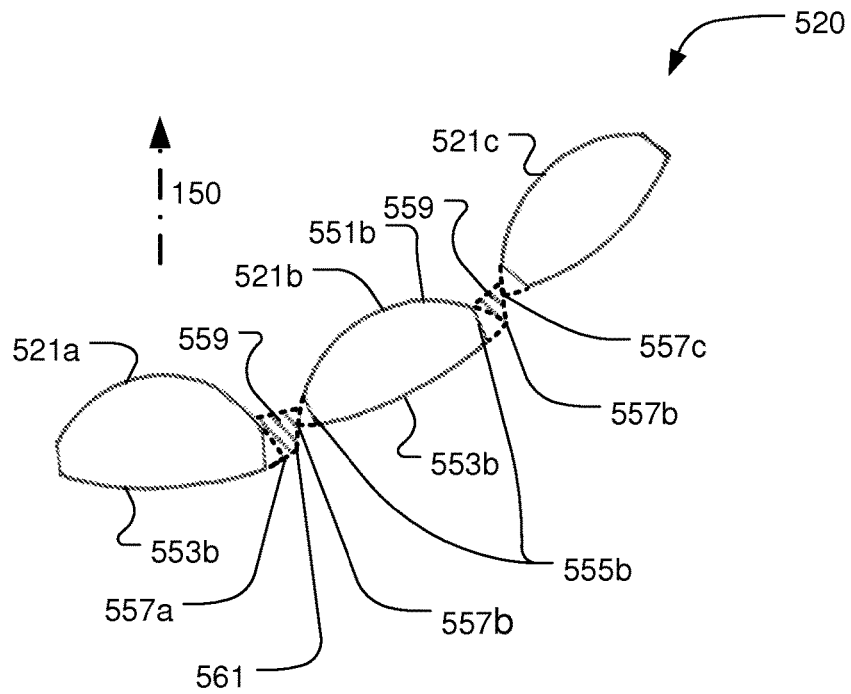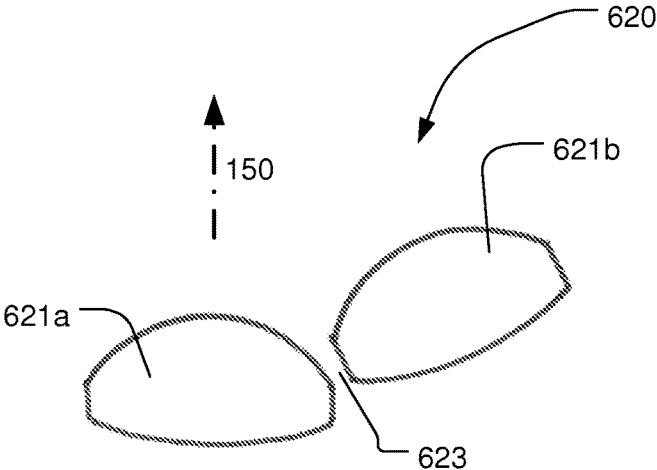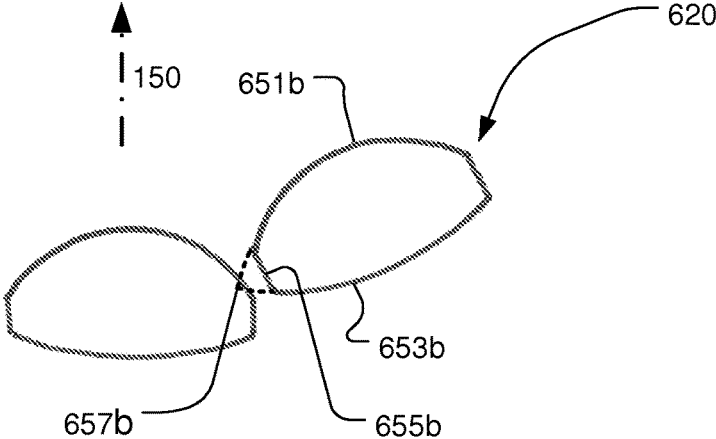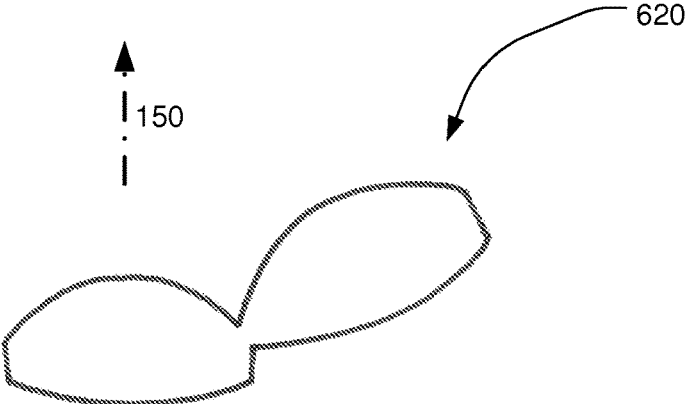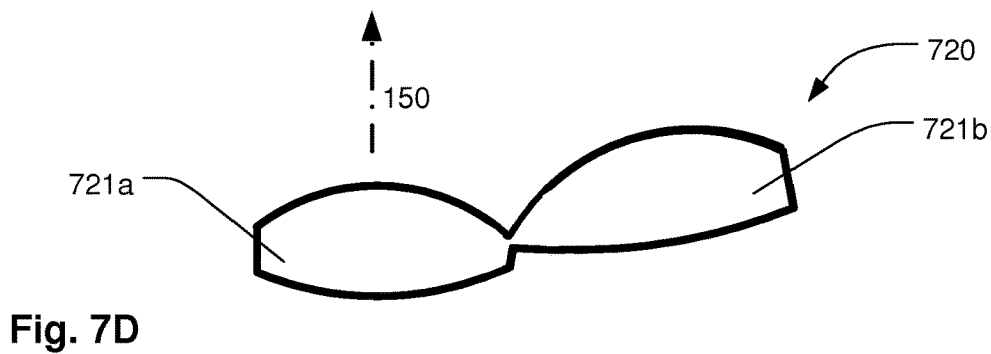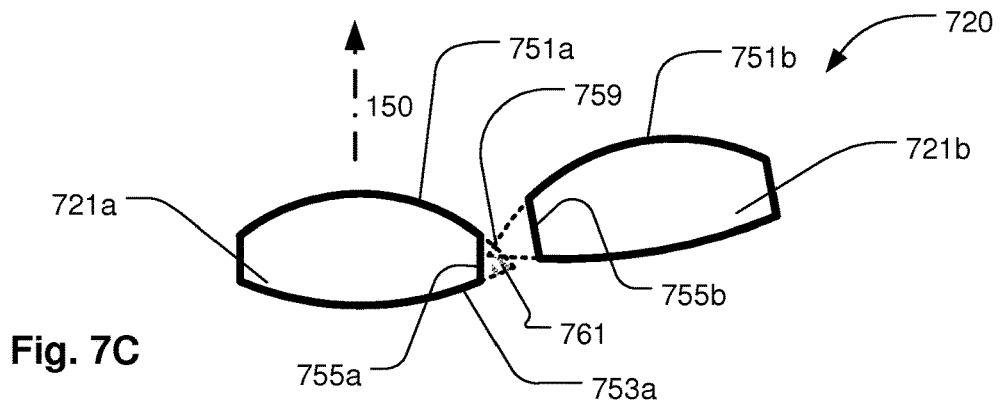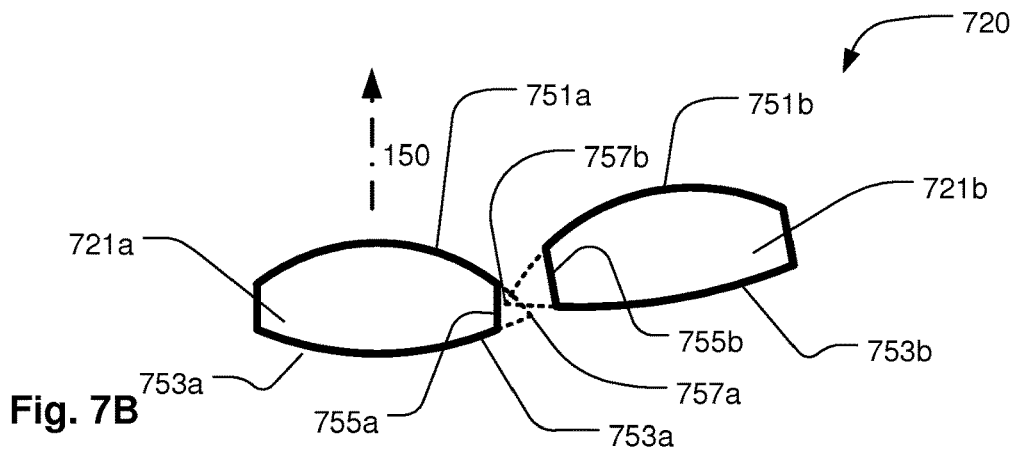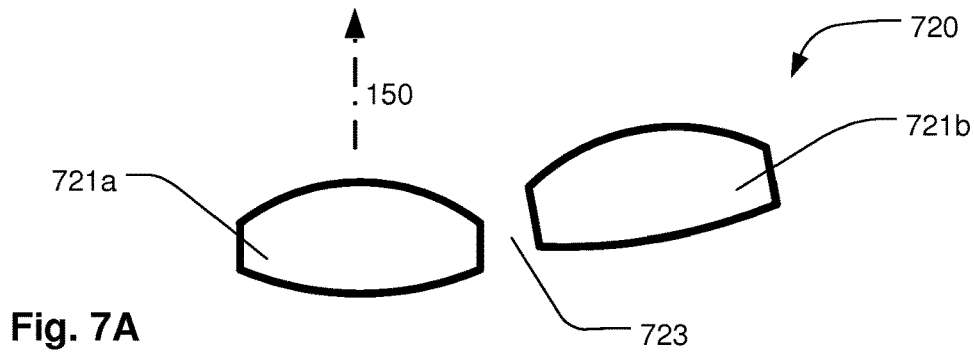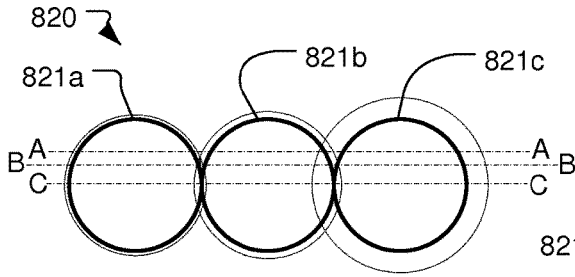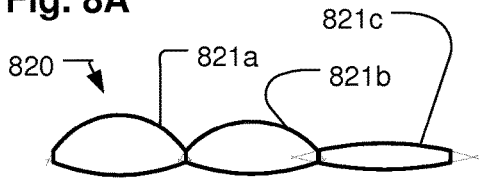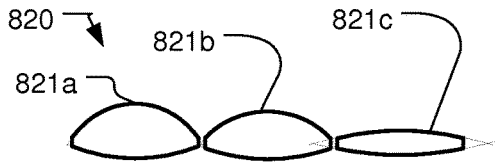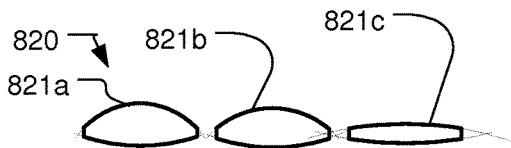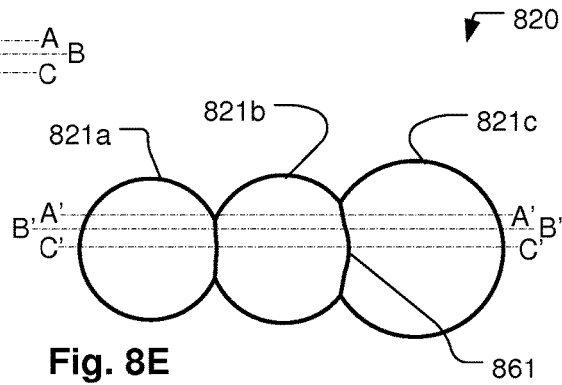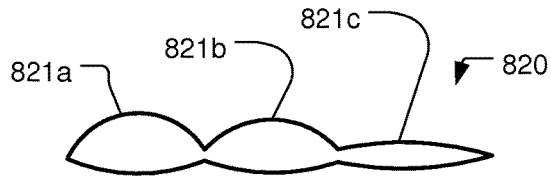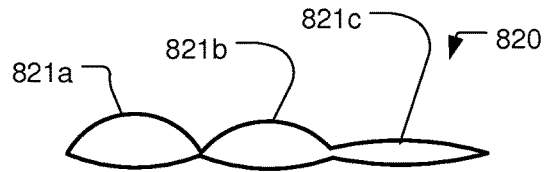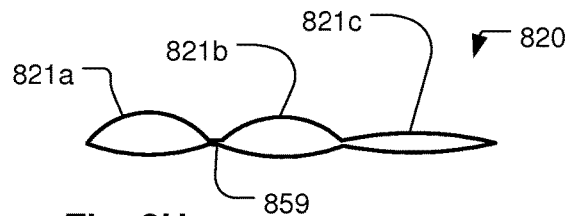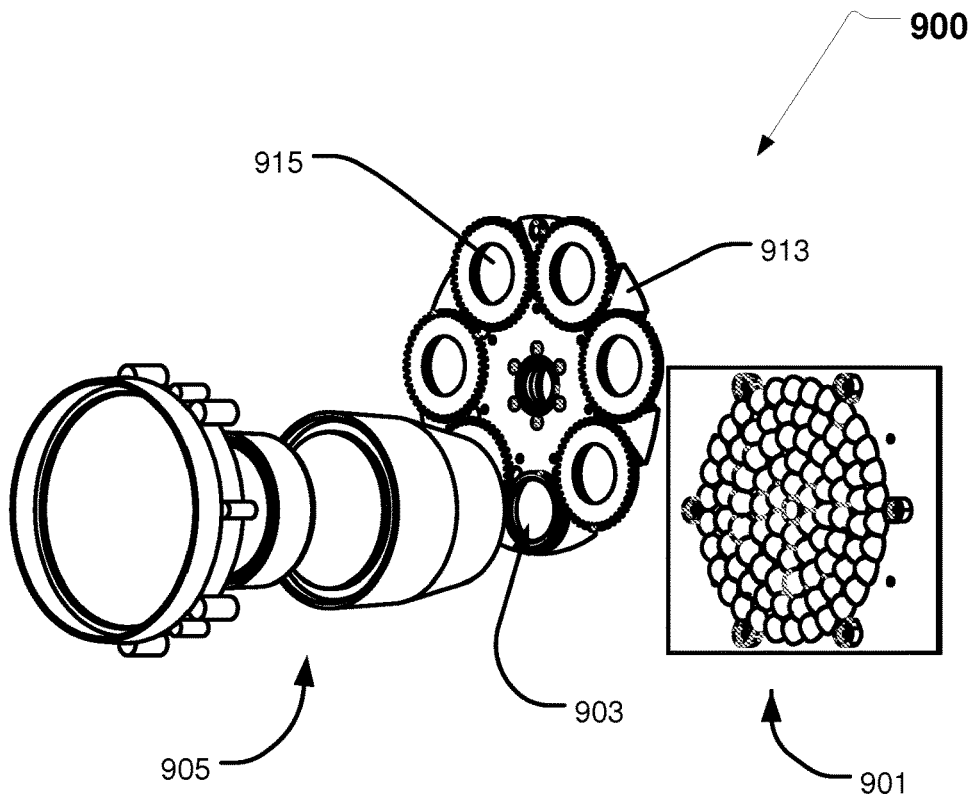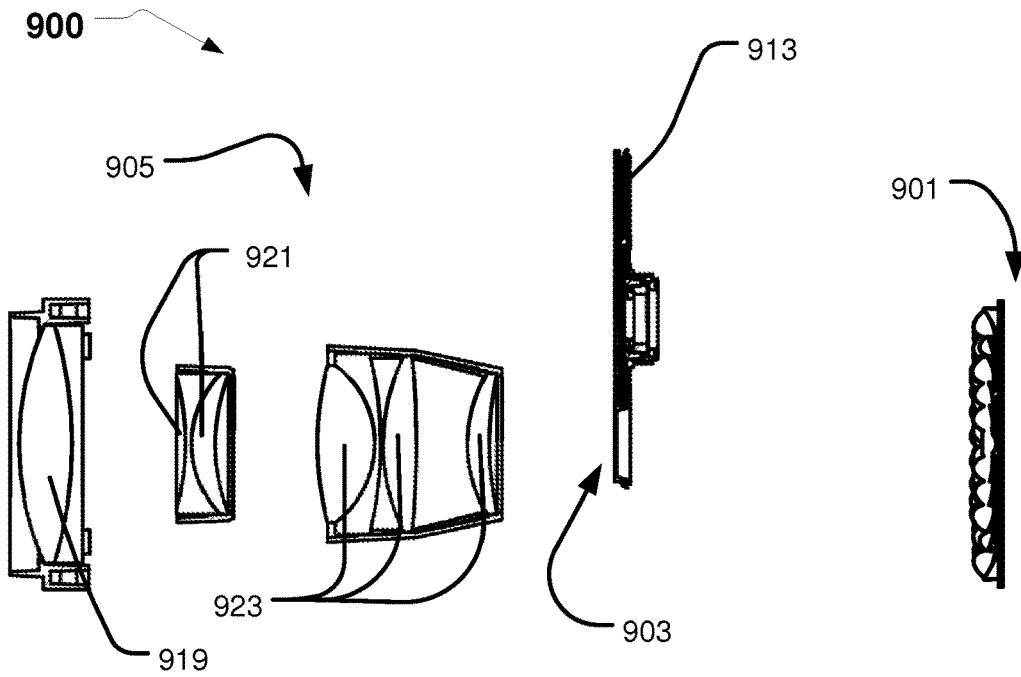
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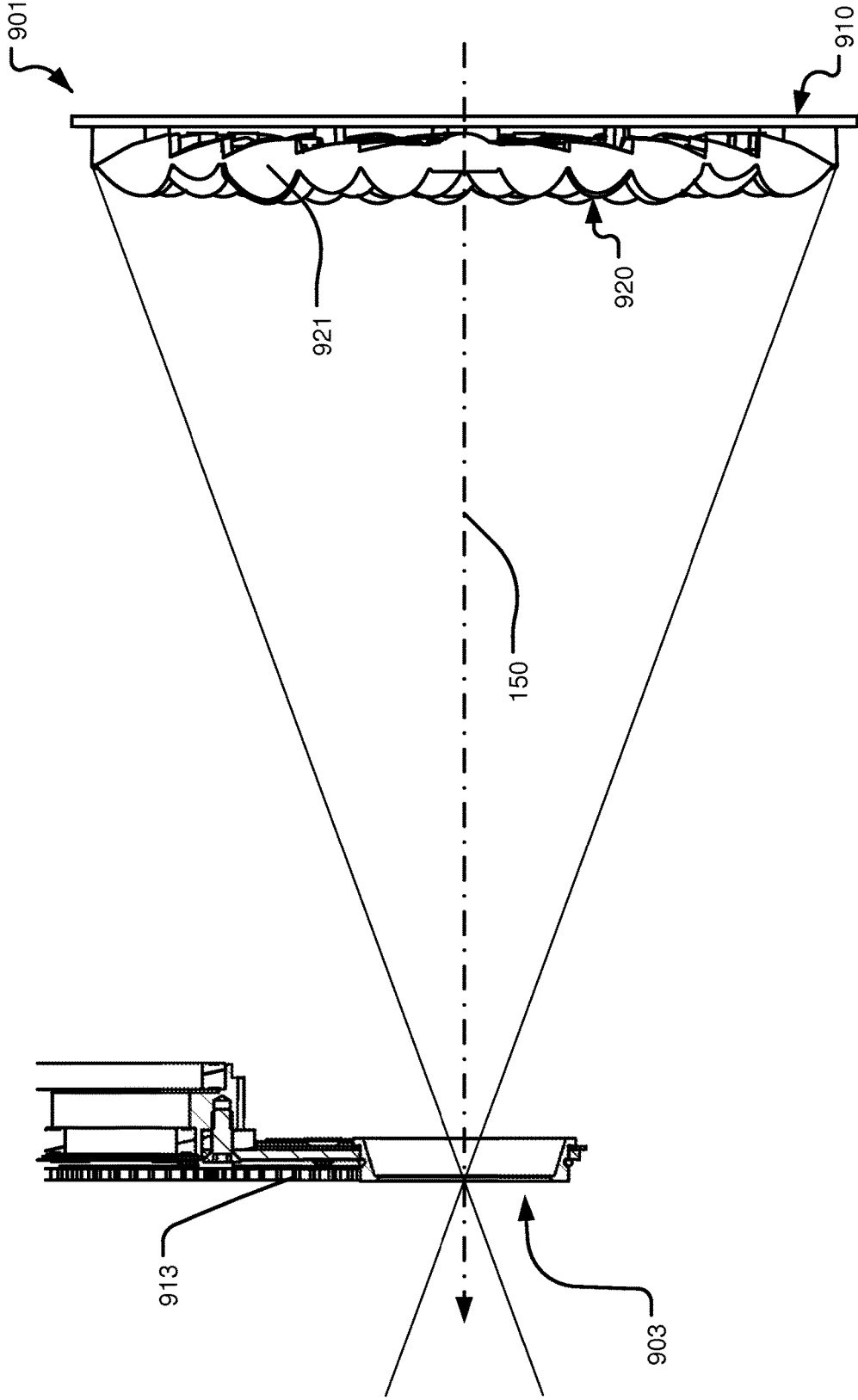
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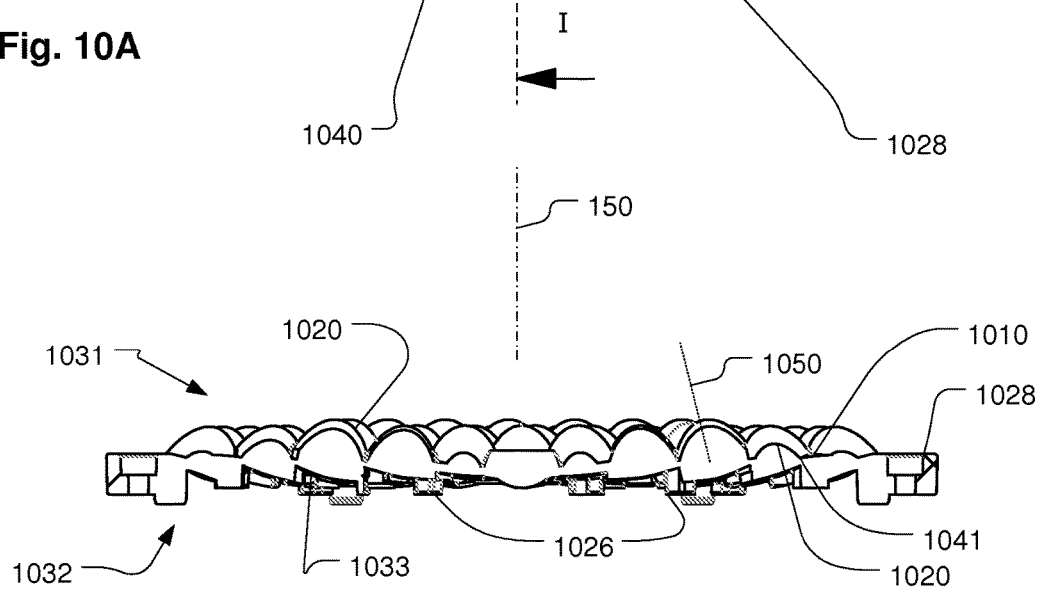
Fig. 10A

Fig. 10B
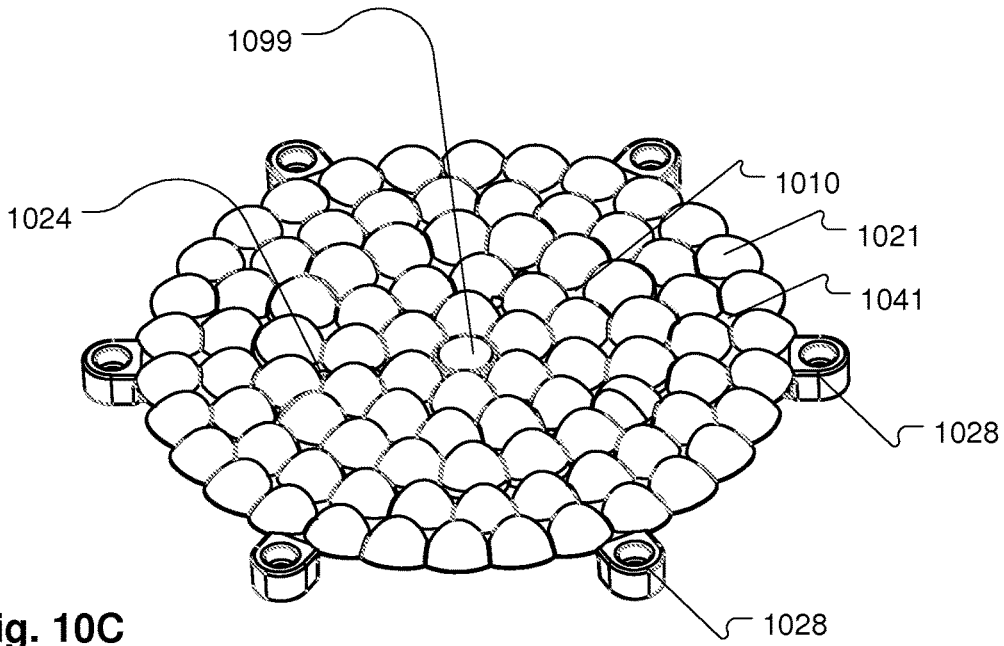
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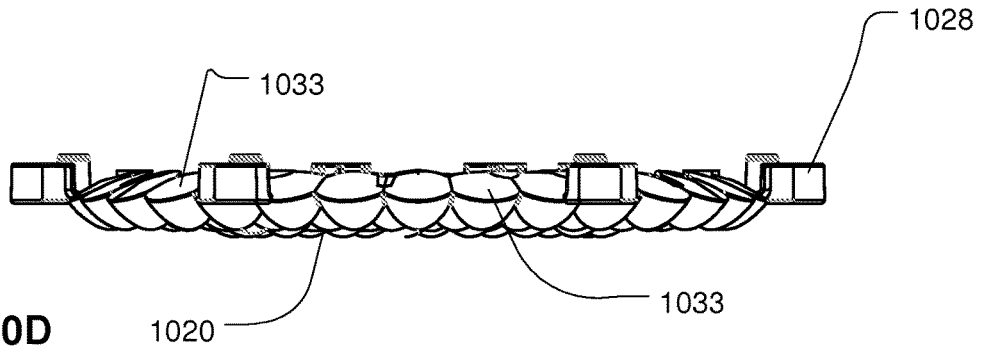
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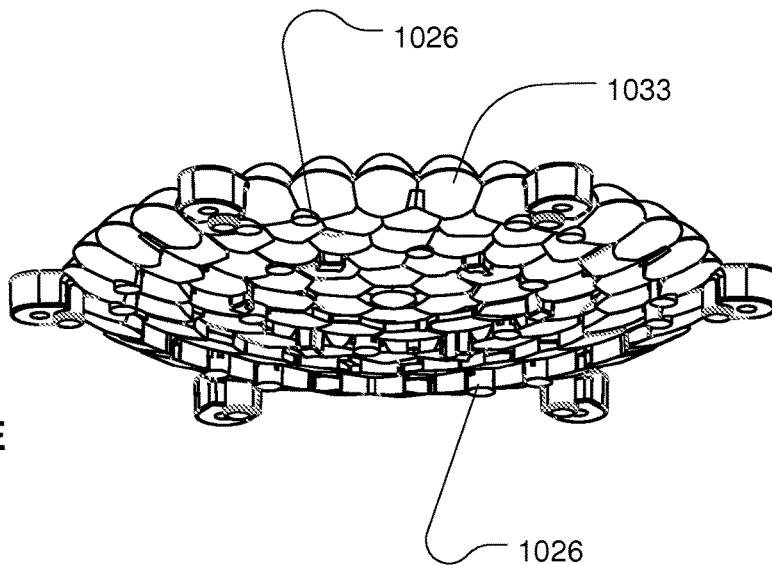
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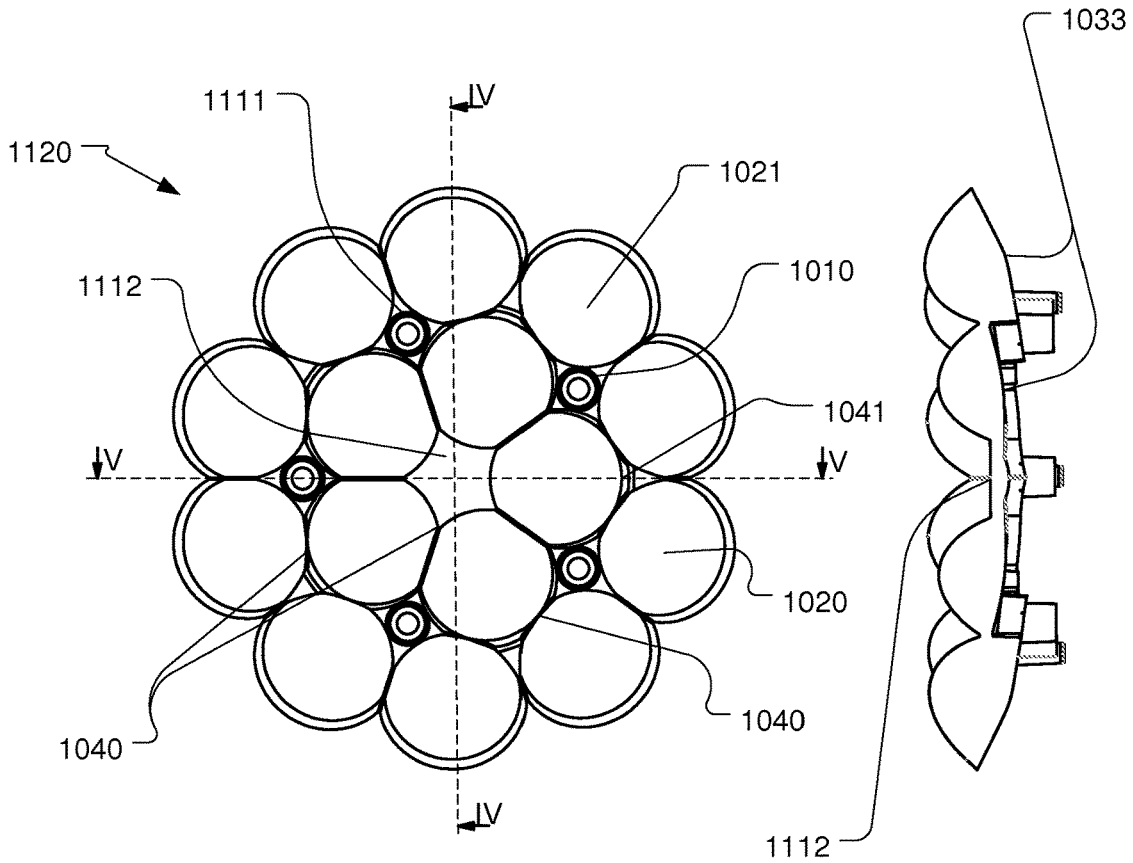
Fig. 11A

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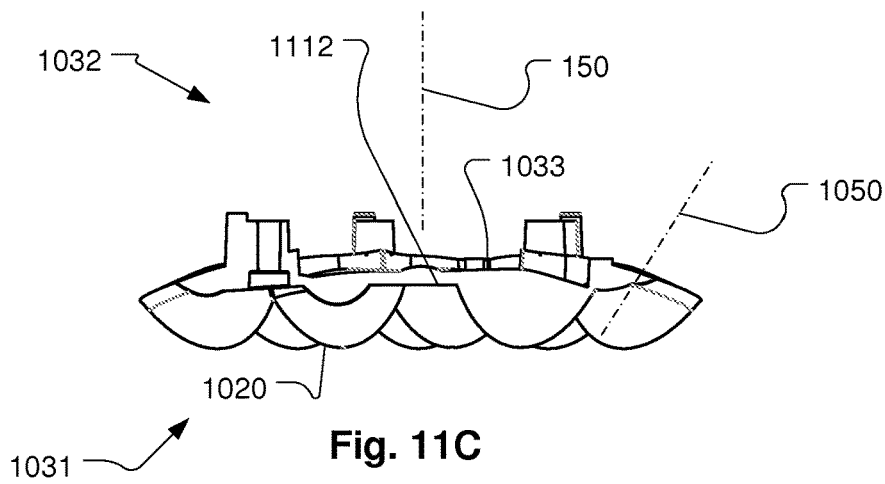
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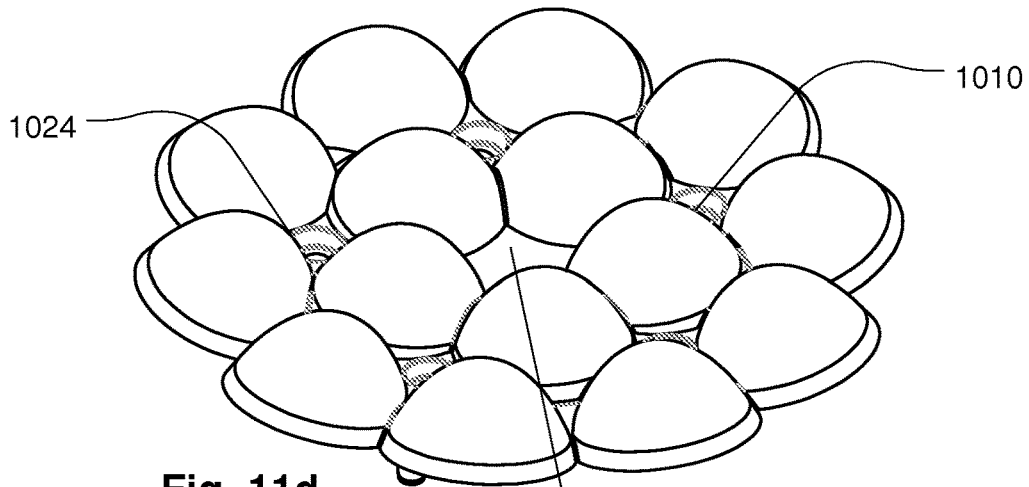
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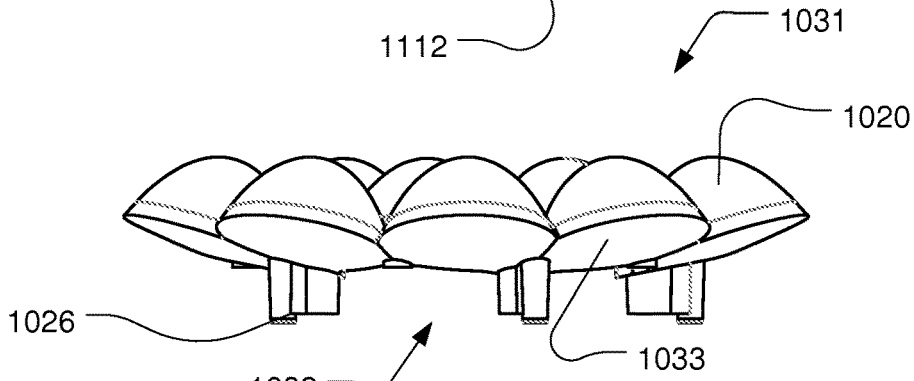
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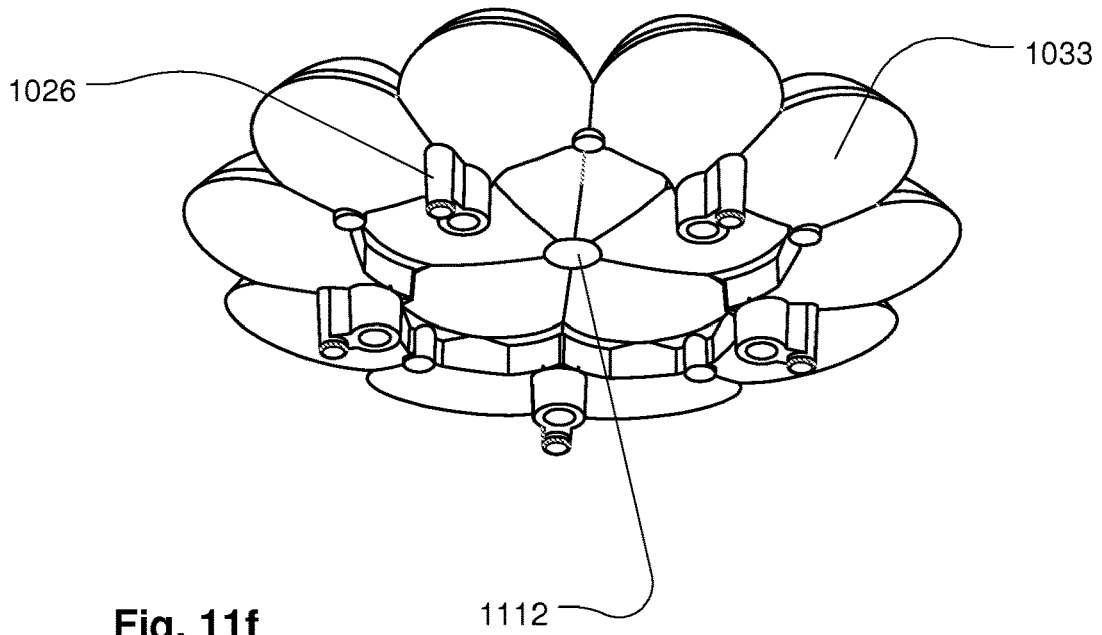
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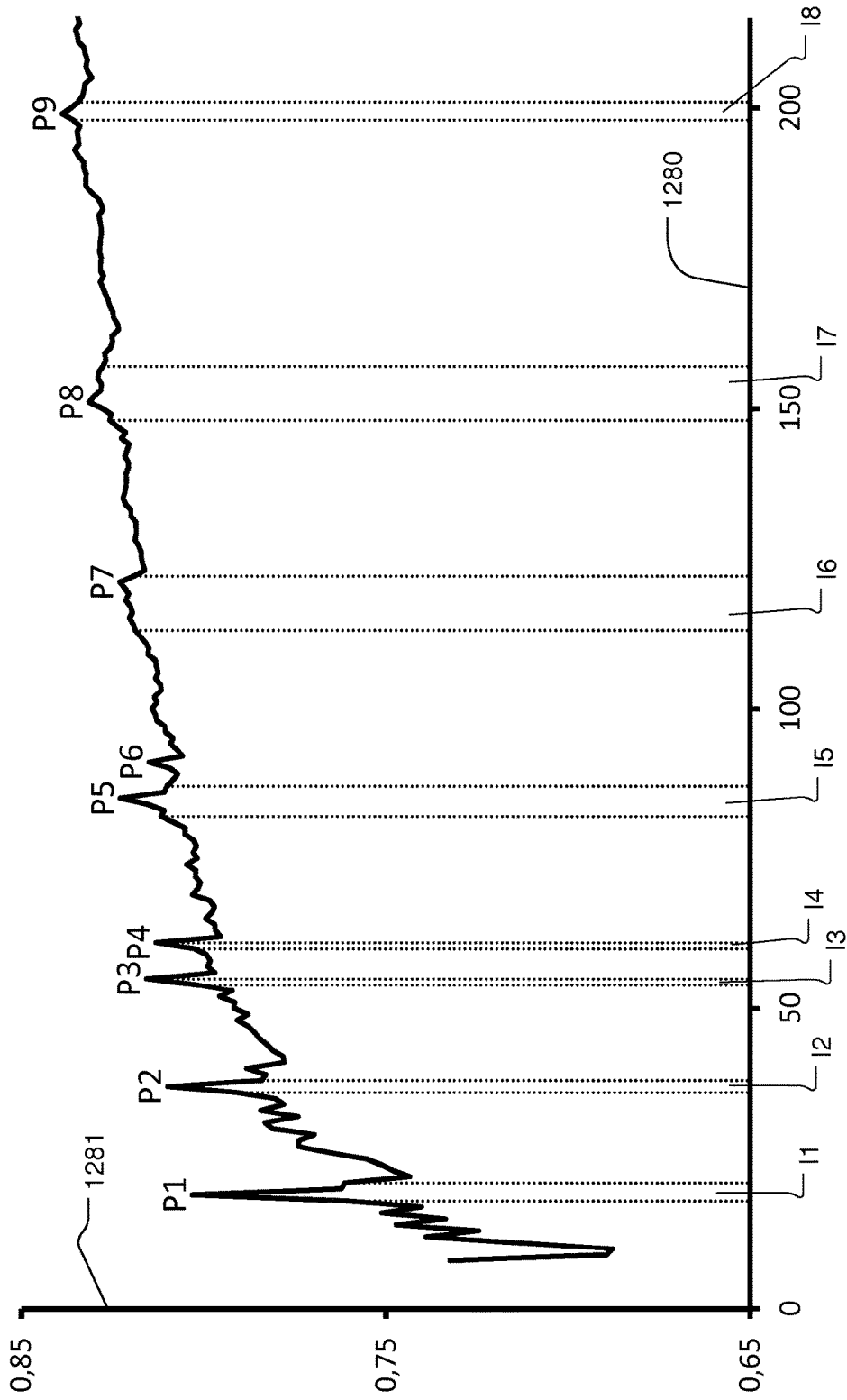
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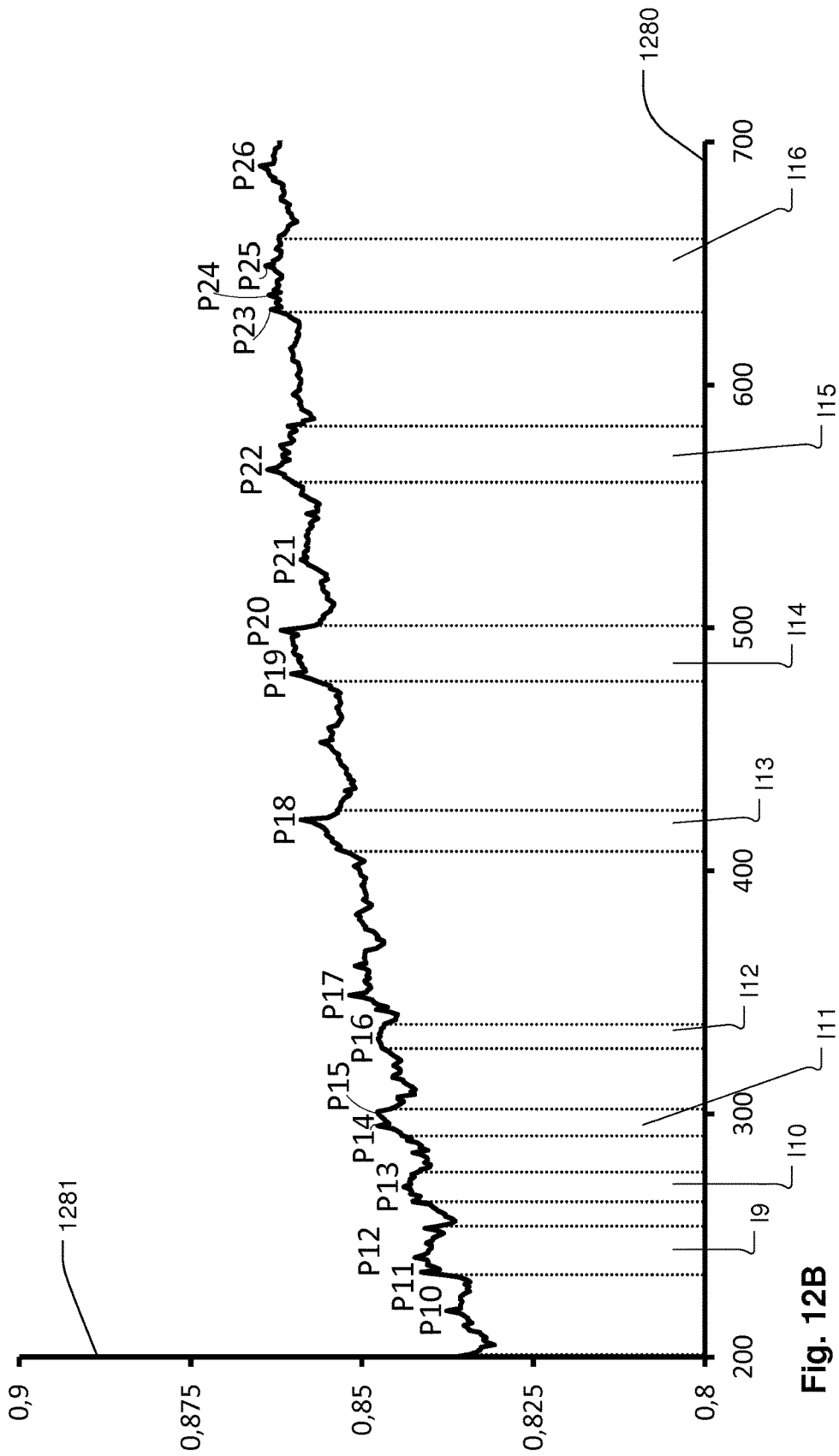
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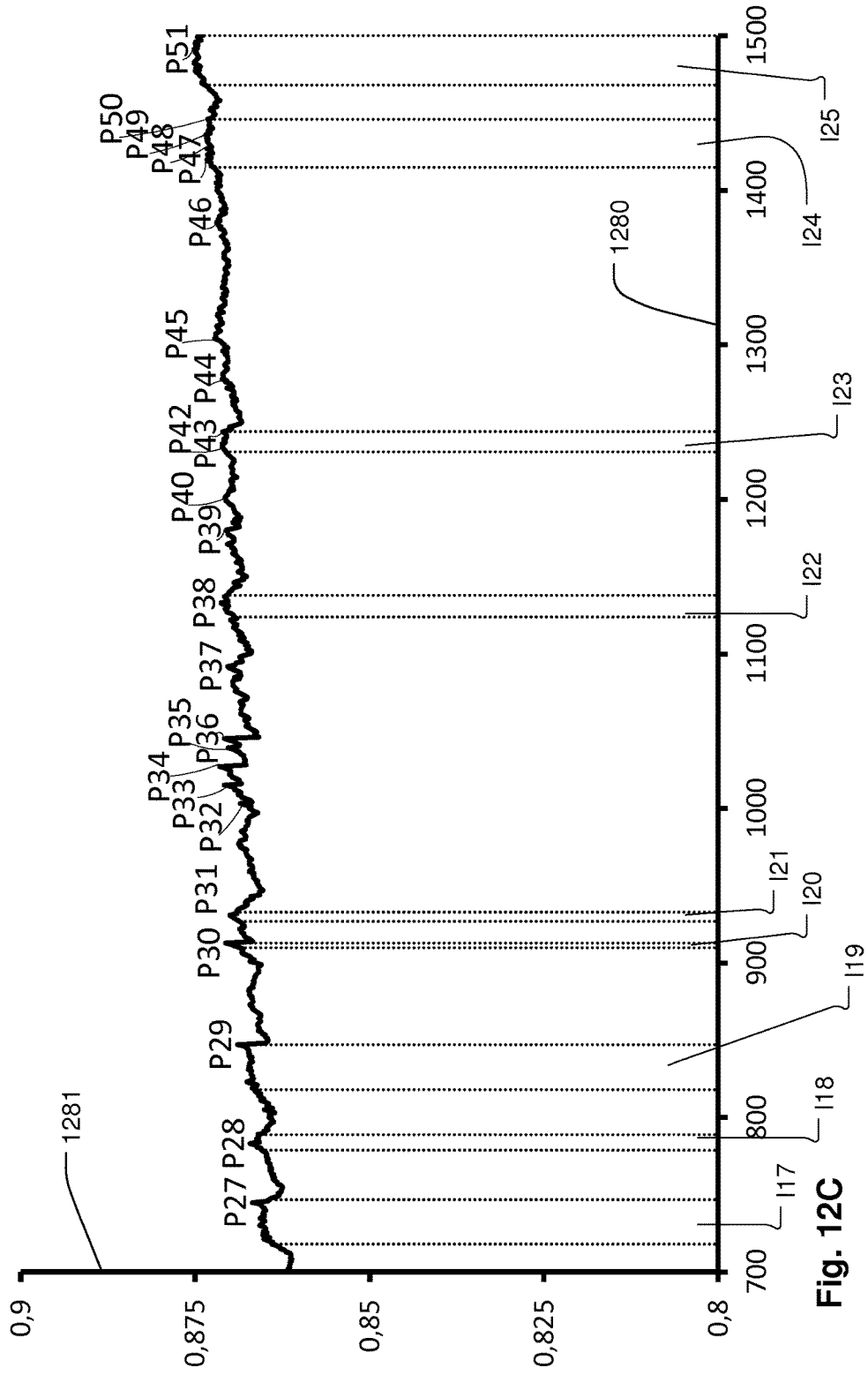
Fig. 12C

LIGHT COLLECTOR WITH A PLURALITY OF LENSLETS PACKED IN AN OPTIMIZED DENSE CIRCULAR PATTERN

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to DK Application No. PA201370745, filed Dec. 5, 2013, the disclosure of which is incorporated in its entirety by reference herein.

TECHNICAL FIELD

The invention relates to optical lenses, particularly optical lenses and lens arrays for collecting light from arrays of light sources.

BACKGROUND

In order to create various light effects and mood lighting in connection with concerts, live shows, TV shows, sport events or as a part of an architectural installation light fixtures creating various effects are getting more and more used in the entertainment industry. Typically, entertainment light fixtures create a light beam having a beam width and a divergence and can for instance be wash/flood fixtures creating a relatively wide light beam with a uniform light distribution or it can be profile fixtures adapted to project images onto a target surface.

Light emitting diodes (LED) are due to their relatively high efficiency, low energy consumption, long lifetime, and/or capability of electronic dimming, becoming more and more used in connection with lighting applications. LEDs are used in lighting applications for general illumination such as wash/flood lights illuminating a wide area or for generating wide light beams e.g. for the entertainment industry and/or architectural installations. For instance like in products like MAC 101™, MAC 301™, MAC 401™, MAC Aura™, MAC Quantum™, Stagebar2™, Easypix™, Extube™, Tripix™, Exterior 400™ series provided by Martin Professional. Further LEDs are also being integrated into projecting systems where an image is created and projected towards a target surface. For instance like in the product MAC 350 Entrour™ provided by Martin Professional.

Different kinds of LEDs are currently commercially available. For instance LEDs may be provided as colored LEDs emitting light having a relatively narrow spectral bandwidth and thus emitting light of a single color. Typically, LED based lighting products include a number of these LEDs of different colors, and light generated by the LEDs provided are combined into an outgoing light beam. The intensity of each color can be adjusted relatively to each other whereby the color of the outgoing light beam can be varied as known in the art of additive color mixing. These lighting products can thus create any color within the color gamut defined by the color of the LEDs. Typically, this kind of lighting products include red LEDs, green LEDs and blue LEDs and are known as RGB lighting products. The RGB lighting products can produce red, green and blue by turning the LED of only one color on while turning the remaining colors off. Further, the RGB products can produce white light by turning all colors on (and approximately at the same intensity) at the same time. However, the color rendering index (CRI) of the white light is very low due the fact that the white light is created by combining light with a narrow spectral bandwidth. The consequence is that an object illu-

minated by this white light, is not reproduced in its natural colors (as it appears when illuminated by sun light).

LEDs are also provided as white LEDs that are adapted to emit light having a broad spectral bandwidth and these may further be provided with different color temperature. These LEDs have a high CRI, as they emitted light over a large spectral bandwidth and are thus used in LED based lighting products to create bright white light, which can be used to illuminate objects and reproduce the objects in substantially its natural color. However, LED based lighting product based on white LEDs cannot create colored light beams without using a color filter as known in the art of subtractive color filtering.

RGBW LED based lighting products, where a number of single color LEDs and a number of white LEDs are combined, are also provided in order to be able to create different colors using additive color mixing and to improve the CRI and the efficacy of the white light. This is achieved by replacing a number of the colored LED with a number of the white LEDs. The white LEDs provide light having a broad spectral bandwidth and the CRI of the white light produced by such device is thus improved by white LEDs and the intensity of the white light is also increased. However the down side is that the intensity of the satiated colors are reduced since there are fewer of these.

The LEDs are also provided in packages having a multiple amount of LED dies emitting light of different color and additionally also a LED die emitting white light. The LED dies can be controlled individual, whereby the relative intensity of the light emitted by each dies may be varied in relation to each other whereby the color of the outgoing light can be varied as known in the art of additive color mixing. Typically, these LED packages includes a red die, green die, blue die and a white die and are known as RGBW 4in1 LEDs. The RGBW 4in1 LED are often used in RGBW LED based lighting products as described above.

In general, it is desired to have a multi-colored LED lighting product with a high lumen and also a high CRI. However, this is hard to achieve with the LED types described above due to Etendue limitations as it is not possible to combine light from an unlimited amount of light sources into a light beam. The known LED based lighting products are as a consequence often designed for spec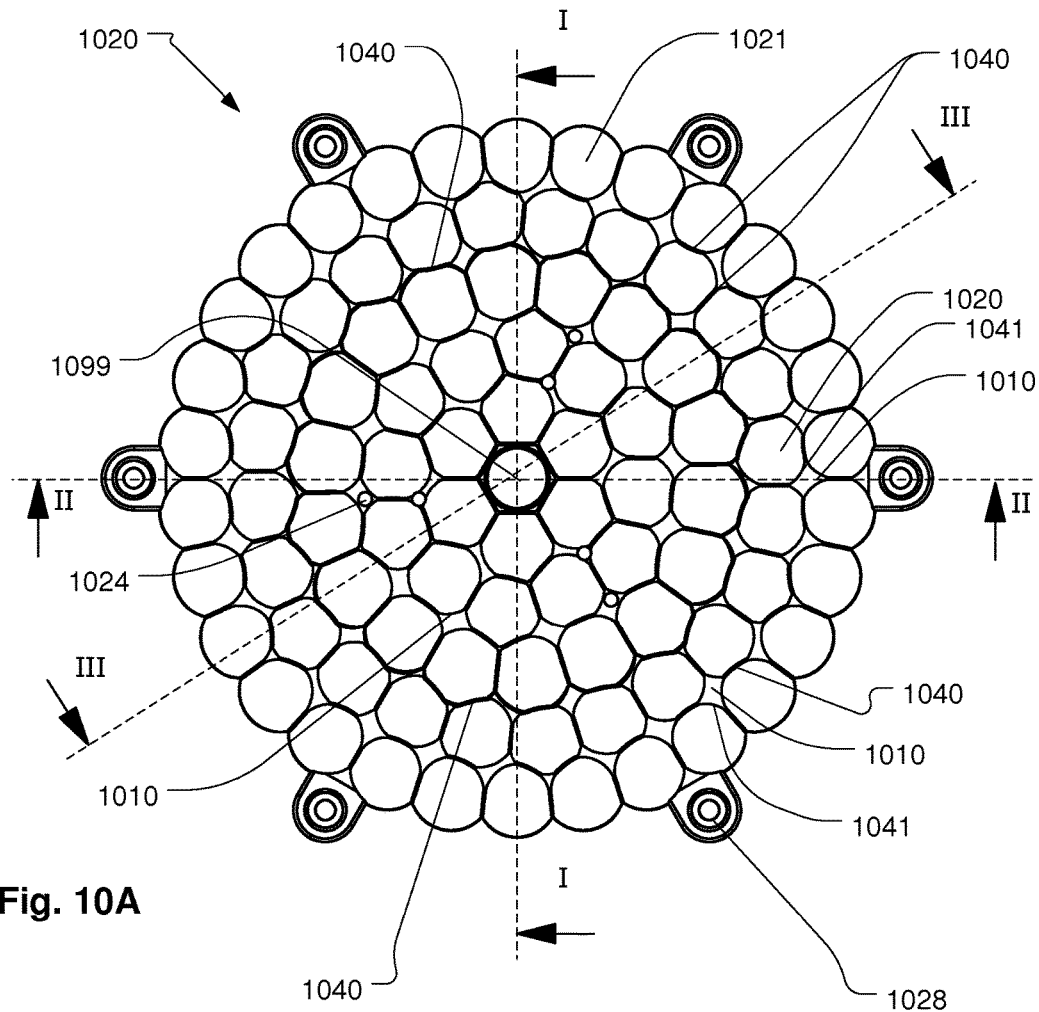ific purposes and it is often necessary to have a large range of LED based lighting products in order to be able to provide a large variety of lighting solutions. This is especially the case in connection with projecting systems, where the light is coupled through an optical gate, where an image creating objects (GOBO) is positioned. An optical projecting system collects the light from the optical gate and is adapted to image the optical gate (and thus also the image creating object) at a target surface. The light beam is very narrow when it passes the optical gate and such projecting systems are thus limited by Etendue. The Etendue, $E=A*\Omega$, at the gate through which light is emitted has a limited opening area A and the imaging optics only collect light from a limited solid angle Ω. For light sources, the Etendue can be calculated in the same way, where A is the radiating area, and Ω is the solid angle it radiates into. Further, it is also desired to have very compact illumination devices, which is difficult to achieve when more light sources are being integrated into the same illumination device.

In projecting systems, the light is generally collected into an optical gate where the image is generated, and an imaging optical system projects the gate onto a target surface. International Publication No. WO0198706, U.S. Pat. Nos. 6,227, 669 and 6,402,347 disclose lighting systems comprising a

number of LEDs arranged in a plane array where a converging lens is positioned in front of the LED in order to focus the light, for instance to illuminate a predetermined area/gate or for coupling the light from the diodes into an optical fiber.

U.S. Pat. Nos. 5,309,277, 6,227,669, International Publication No. WO0198706, Japanese Publication No. JP2006269182 A2, European Publication No. EP1710493 A2, U.S. Pat. No. 6,443,594 disclose lighting systems where the light from a number of LEDs is directed towards a common focal point or focusing area, for instance by tilting the LEDs in relation to the optical axis (Japanese Publication No. JP2006269182 A2, International Publication No. WO0198706, U.S. Pat. No. 5,309,277) or by using individually refracting means positioned in front of each LED (U.S. Pat. Nos. 6,443,594, 7,226,185B, European Publication No. EP1710493).

International Publication No. WO06023180 discloses a projecting system comprising a LED array with a multiple number of LEDs where the light from the LEDs is directed towards a target area. The LEDs may be mounted to a surface of a curved base.

The prior art fixtures try to increase the lumen output by adding as many light sources as possible. The consequence is, however, that the efficiency with regard to power consumption versus light output is very low, as it is fundamentally only possible to effectively utilize light sources of same or less Etendue as the imaging optics in this kind of optical system. So if the source Etendue is a close match to the Etendue of the imaging system there are no gains in using multiple sources in order to increase the light output (intensity/lumen) as the Etendue of the light sources then will be larger than the Etendue of the imaging system and the imaging system is thus not capable of collecting the light.

International Publication Nos. WO11076213 and WO11076219 disclose an illumination device comprises a light source module generation light, an aperture delimiting the optical gate and a projecting system adapted to image the optical gate at a target surface. The light source module comprises a number of light sources and a number of light collecting means. The light collecting means comprise a central lens aligned along and a peripheral lens at least partially surrounding the central lens. The central lens collects and converts a first part of the light from the light source images the light source between the aperture the projecting system. The peripheral lens part collects and converts a second part of said light from said light source and is adapted to concentrate said second part of said light at said aperture. The light source module comprises a cooling module including a number of interconnected plane mounting surfaces angled in relation to each other and where the light sources is arranged on said plane mounting surfaces. The cooling module comprises a first side including the mounting surfaces and a second side including a number of cooling fins defining a number of radial air channels.

Even though the illumination device disclosed by International Publication Nos. WO11076213 and WO11076219 is very effective, it has some disadvantages as it is relatively expensive to manufacture as the LEDs and TIR lenses needs to be arranged individually.

SUMMARY

The object of the present invention is to solve the above described limitations related to prior art or other problems of the prior art. This is achieved by an illumination device and method as described in the independent claims. The depen-

dent claims describe possible embodiments of the present invention. The advantages and benefits of the present invention are described in the detailed description of the invention.

In summary, the invention relates to a light collector with a plurality of lenslets arranged in a dense circular pattern wherein the dense pattern has a circular outer periphery. The lenslets are configured to collect light from a corresponding plurality of light sources and to direct the collected light towards a gate or aperture contained in an illumination device. The illumination device comprises a light unit with the light sources, the light collector, the gate and an optical projecting system for projecting the light from the gate or image light from the gate towards a distant object such as a wall or screen.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be described, by way of example only, with reference to the drawings, in which

FIGS. 1A-1B illustrate an illumination device and a light collector used with the illumination device;

FIGS. 2A-2C illustrate different axial positions of the lenslets, different radial positions of lenslets relative to light sources, different tilt angles of lenslets relative to the optical axis;

FIGS. 3A-3C illustrate a curved hexagonal dense circular packaging of lenslets;

FIGS. 4A-4L illustrate dense circular packings of 15, 24, 36, 37, 60, 61, 90, 91, 121, 151, 199, and 235 lenslets;

FIGS. 5A-5E illustrate principles for growing lenslets so that lenslets merges;

FIGS. 6A-6C illustrate other principles for growing lenslets so that lenslets merges;

FIGS. 7A-7D illustrate other principles for growing lenslets so that lenslets merges;

FIGS. 8A-8H illustrate other principles for growing lenslets so that lenslets merges;

FIGS. 9A-9C illustrate an illumination device comprising a light unit and a light collector according to the present invention;

FIGS. 10A-10E illustrate views of a light collector with 90 lenslets;

FIGS. 11A-11F illustrate views of a light collector with 15 lenslets;

FIGS. 12A, 12B and 12C illustrate graphs of the packing density of circular lenslets packed in a circle, as a function of the number of lenslets.

DETAILED DESCRIPTION

As required, detailed embodiments of the present invention are disclosed herein; however, it is to be understood that the disclosed embodiments are merely exemplary of the invention that may be embodied in various and alternative forms. The figures are not necessarily to scale; some features may be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention.

FIG. 1A illustrates a cross sectional view through the center of an illumination device 100 (indicated by dash-dotted line A-A in FIG. 1b). The illumination device comprises light unit 110 with a plurality of light sources 111, a

light collector **120** with a plurality of lenslets **121**, a gate **130** and an optical projecting system **140**.

The light sources **111** may be in the form of light emitting diodes (LEDs), discharge lamps, organic light emitting diodes (OLEDs), PLED's, plasma sources, filament lamps, fluorescent light sources, phosphor based light sources, or other suitable light sources. A single light source **111** may contain one or more light sources units, for example, two or more light source units with different colors. For example, a light source may contain one light emitter for emitting e.g. white light, may contain three light emitting diodes with red, green and blue dies (known as a RGB 3in1 LEDs) or may contain four light emitting diodes with red, green, blue and white dies (known as a RGBW 4in1 LEDs).

The lenslets **121** are adapted to collect light from the light sources **111** and to convert the collected light into a plurality of light beams **127**, **128** (not all shown) propagating along an optical axis **150**.

It is understood that light beams **127**, **128** propagating along the optical axis contain rays of light propagating at an angle, for example, an angle less than 45 degrees, to the optical axis. Accordingly, a vector representing a ray propagating along the optical axis contains a vector component which is parallel with the optical axis and a vector component which is perpendicular to the optical axis where the parallel vector component is larger than the perpendicular vector components.

The lenslets **121** may be configured to fill the gate **130** with light from the light sources **111** so that the area, i.e., the aperture, of the gate **130** is illuminated with a uniform intensity or optimized for max output. The gate **130** is arranged along the optical axis **150** and may be shaped as a circular aperture in an opaque plate.

The optical projecting system **140** may be configured to collect at least a part of the light beams **127**, **128** transmitted through the gate **130** and to image the optical gate at a distance along the optical axis. For example, the optical projecting system **140** may be configured to image the gate **130** onto some object such as a screen, for example, a screen on a concert stage. A certain image, for example, some opaque pattern provided on a transparent window, an open pattern in a non-transparent material, or imaging object such as GOBOs known in the field of entertainment lighting, may be contained within the gate **130** so that that the illuminated image can be imaged by the optical projecting system **140**. Accordingly, the illumination device **100** may be used for entertainment lighting.

Embodiments of the present invention relate primarily to the configuration of the light collector **120** and the configuration thereof in relation to the light unit **110** and the gate **130**.

FIG. 1B illustrates the light collector **120** in a top view seen from the gate **130**. Each lens is represented by a circle which corresponds to the footprint of a circle. Thus, each of the lenslets has a footprint of substantially uniform circular cross section and substantially equal size or footprint-area. The footprint of a lenslets refers to the basic form of the lenslets, however the actual shape of the lenslets may deviate from the circular footprint for instance due to grow of the lenslets as described elsewhere in the present application. Further, the lenslets **181** are arranged in a dense circular pattern as described elsewhere herein, i.e., so that a circumscribing circle **180** can be defined which connects with all of the outermost circles or lenslets **181** having the same distance **170** to the center of the light collector **120**. There may be one lenslet **181** for each light source **111** (shown in FIG. 1A) so that there is a one-to-one correspon-

dence between lenslets **181** and the light sources **111**, i.e., so that each light source has an associated lenslet. However, one light source may contain one or more light source units possibly integrated into a single light source device such as a 3in1 or a 4in1 LEDs.

As an effect of the dense packing, the lenslets may be arranged in a number of rings **181**, **182**, **183** around the center **190** of the circumscribing circle **180**. Accordingly, the lenslets may comprise a plurality of outermost adjacent lenslets with their center at the outermost ring **181** and located along an outer circular boundary **180**. The outermost lenslets have the same radial distance **170** to a center of the light collector **120** or to a center of a center lenslet.

Lenslets located along the second outermost ring **182** may appear to be arranged at the same distance from the center **190**, however in order to accomplish dense circular packaging, the lenslets in second outermost ring are actually arranged in an annular ring, where the annular rings are delimited by two concentric rings **182a** and **182b** (illustrated by thin dotted lines). The annular ring **182** comprises at least two set of lenslets, where each set of lenslets comprise a number lenslets having the same radial distance to the center of the light collector and where the radial distance to the center of the light collector are different for the two set of lenslets.

In the illustrated embodiment, every second lenslet in the annular ring **182** is arranged at the same distance from the center **190** of the light collector and arranged respectively with it's center at the first concentric ring **182a** and the second concentric ring **182b**, indicated at the inner and outer side of the circle **182**. The second outermost ring comprises thus two set of lenslets, where each set of lenslets is arranged at the same radial distance from the center **190** of the circumscribing circle light collector. For instance, the first set of lenslets comprises the lenslets labeled with a and the lenslets of the second set of lenslets comprises the lens lets with β. Compared to the prior art where the hexagonal packaging of lenslets is considered as being most optimized, packaging some of the lenslets by packing the lenslets in annual rings as described above results it the fact that a more dense packing can be provided, as some lenslets encircling the center lenslet can be moved closer to the center and thereby utilize more of the dead space between the lenslets and thus be squeezed together. Where the dead space constitutes the areas of the light collector without lenslets.

Lenslets (or sets of lenslets) belonging to the same annular ring may be defined as lenslets having roughly the same radial distance to the center of the light collector, where roughly the same radial distance means that the difference between the radial distance of the outermost lenslet and the radial distance of the innermost lenslet is less than the half diameter of the lenslets. Lenslets located along one of the same one of the rings **182-183** except for the outermost circle **181** can be said to have at roughly the same radial distance to the center as can be verified from tables 1a-11. Lenslets located at the outermost circle can be said to have the same radial distance to the center which can also be verified from tales 1a-11.

The present invention relates also to a method for manufacturing a light collector adapted to collect light from a plurality of light sources, wherein the light collector comprises a plurality of lenslets adapted to collect light from the light sources and further adapted to convert the collected light into a plurality of light beams so that the light beams propagate along an optical axis, wherein each lenslet comprises an entrance surface where the light enters the lenslet and an exit surface where the light exits the lenslet, and

wherein each lenslet has a substantial uniform circular cross section of the lenslet. The method comprises:

arranging the lenslets in a dense pattern, wherein the lenslets comprise a plurality of outermost lenslets located along an outer circular boundary, wherein each of the outermost lenslets has the same radial distance to a center of the light collector, and

optimizing a packaging density defined by a ratio of a sum of areas of the circular cross sections of the lenslets and an area of the outer circular boundary.

FIG. 2A illustrates an embodiment in which the axial distances 201a and 201b between the lenslets 221a, 221b and the associated light sources 211a, 211b along the optical axis 150 for adjacent lenslets 221a, 221b are different for at least some of the adjacent lenslets.

The axial distances 201a and 201b may depend on a radial distance 270a and 270b from the lenslets or the corresponding light source to a center of the light collector or to the optical axis 150. Lenslets having the same radial distance to the center or optical axis have the same axial distance. Thus, lenslets having different radial distances or lenslets located along different rings 181-183 may have different axial distances and the different sets of lenslets in the annular rings may also have different axial distance.

The different axial distances may enable a suitable imaging of a light source 211 towards the gate 130 so that an imaging fills the gate 130 optimally and so that the imaging does not exceed the border of the gate 130.

The greater the radial center distance 270a; 270b for a lenslet is, the greater the distance is from the lenslet to the gate 130. The different distances from lenslets 22a1 and 222a to the gate 130 implies that the axial distances 201 need to be different in order to enable a suitable imaging of a light source 211 towards the gate 130.

Accordingly, in an embodiment wherein the axial distances 201 depend on a radial distance 270 from one of the adjacent lenslets to a center of the light collector or to the optical axis, lenslets having the same radial distances 270 to the center or lenslets located along the same ring 181-183 may also have the same axial distances 201.

The axial distances 201 may be within the range from 0 to 10 millimeters.

Additionally or alternatively to different axial distances 201 between the lenslets and light sources, at least some of the light sources 111 may be displaced relative to the associated lenslet 121 in a direction perpendicular or substantially perpendicular to the optical axis 150, for example, in a radial direction relative to the center of the light collector or optical axis. The displacement may be in a form so that the center of a light source 111 is displaced relative to the center of an associated lenslet 121 as shown by displacement 230a and 230b in FIG. 2B. The relative displacement of the light source 211 in a plane (perpendicular to the optical axis 150) of the light unit 210 may have the effect that a ray 231 being substantially parallel with the optical axis 150 is deflected into ray 232. Thereby, the displacement 230a and 230b may be chosen so that light 231 from light sources is directed towards the gate 130.

The relative displacement 230 may be within the range from 0 to 5 millimeters.

In an embodiment, the displacement (e.g., radial displacement) between one of the light sources and the associated lenslet increases as a function of a radial distance 170 from the associated lenslets to a center of the light collector or the optical axis. Thereby, the larger the radial distance 170 is for a light source 111, the larger is the displacement and, thereby, the deflection-angle towards the optical axis 150.

As illustrated in FIG. 2C, additionally or alternatively to different axial distances 201 (shown in FIG. 2A) between the lenslets and light sources and the relative displacement 230 (shown in FIG. 2B), optical axes 240a, 240b (in dotted line) of at least some of the lenslets may be angled by an angle 241a, 241b relative to the optical axis 150 of the light collector 120. The angling may improve the imaging of light from the light sources 121 onto the gate 130. Generally, the angling is within the range from 0 to 30 degrees and the angling is oriented so that the lenslets points towards the optical axis, i.e., so that lenslets located above the optical axis 150 is rotated clock-wise and lenslets located below the optical axis 150 is rotated counter clock-wise.

In an embodiment, the angle 241 of the angled lenslets depends on a radial distance 170 from one of the lenslets to a center of the light collector or the optical axis so that lenslets having different radial distances or lenslets located along different rings 181-183 may be angled different and the different sets of lenslets in the annular rings may also have different angles. Thus, the larger the radial distance 170 is for a lenslet, the larger the angle 240 may be in order to provide optimal imaging of the light sources onto the gate 130.

Additionally or alternatively to different axial distances 201, for different relative displacements 230 and for different angles 240, the lenslets 121 may have different optical properties, such as, for example, properties that are in the form of different optical powers. The possible different optical powers or shape of the lens that deviate from spherical surfaces are determined so as to obtain a suitable or optical imaging of the light sources onto the gate 130, i.e., so as to optimize the efficiency and/or uniformity of the intensity in the gate 130.

In general, a suitable or optimal imaging of the light sources onto the gate 130 may be satisfied when the gate 130 is filled with light from a light source in a way so that the gate is filled with light having intensity variations below a given percentage and/or so that a given percentage of the power from a light source is transmitted through the gate 130.

Due to one or more of different axial distances 201 (shown in FIG. 2A) between the light sources 211 and the lenslets 221, displacements 230 (shown in FIG. 2B) between the light sources 211 and the lenslets 221 perpendicular to the optical axis, angling of lenslets 221 relative to the optical axis 150 and lenslets 221 having different optical powers of, the light sources 211 can be imaged or projected onto the gate 130 so that the gate is properly filled with a uniform intensity distribution. This arrangement of the lenslets may be particularly advantageous when the light sources 211 are arranged in a flat plane, for example, on a plane printed circuit board as such solution may make manufacturing of the illumination devise simpler and cheaper. Accordingly, in an embodiment, the light unit 210 may be configured as a plane or a flat unit in which all of the light sources 211 are located on the same plane.

As described in connection with FIG. 1B, the lenslets 121 are arranged in a dense circular pattern. The inventor has realized that arranging the lenslets in a pattern which is both dense (i.e., wherein the ratio of areas of lenslets and the area of the circumscribing circle is improved in comparison with a non-dense pattern) and circular is advantageous since the dense pattern may improve the percentage of light-power transmitted through the light collector 120 and illumination device 100. Further, the imaging lens has a circular aperture, that ideally should be filled to the edge and dense circular pattern optimizes this whereby the efficiency is improved.

The circular pattern may be advantageous to non-circular patterns since a circular image projection on a wall may have a more attractive visual appearance in comparison to non-circular image projections. Further, the circular packing makes it possible to use an axial symmetric projecting system without too much loss of light which simplifies the optical design and reduces costs of the projecting system.

The problem of arranging circles of the same size in a dense circular pattern has been described in the references (1) "R. L. Graham, B. D. Lubachevsky, Dense packings of 3k(k+1)+1 equal disks in a circle for k=1, 2, 3, 4 and 5, Proc. First Int. Conf. "Computing and Combinatorics" COCOON'95, Springer Lecture Notes in Computer Science 959 (1996), 303-312" and (2) "B. D. Lubachevsky, R. L. Graham, Curved Hexagonal Packings of Equal Disks in a Circle, Discrete Comput. Geom. 18 (1997), 179-194" which are hereby incorporated by reference. The incorporated references describe how a dense pattern can be obtained generally for any number of circles and specifically when the number of circles equals a hexagonal number h(k):

$$h(k)=3k(k+1)+1, \text{ wherein } k \text{ is an integer} \qquad \text{(Eq. 1)}$$

The incorporated references (1) and (2) describe that the dense pattern for a general number of circles can be obtained through an optimization method wherein a packaging density is optimized using a known computer based "billiards" simulation algorithm. The packaging density is defined by a ratio of a sum of areas of the circles and an area of an outer circular boundary circumscribing the circles.

The "billiards" simulation algorithm is described in (3) "B. D. Lubachevsky, How to simulate billiards and similar systems, J. Computational Physics 94 (1991), 255-283"; (4) "B. D. Lubachevsky and F. H. Stillinger, Geometric properties of random disk packings, J. Statistical Physics 60 (1990), 561-583" and (5) "R. L. Graham and B. D. Lubachevsky, Dense packings of equal disks in an equilateral triangle: from 22 to 34 and beyond, The Electronic Journ. of Combinatorics 2 (1995)". These three references are also incorporated by reference.

The incorporated references as noted above (i.e., (1) and (2)) describe that the dense pattern for a hexagonal number can be obtained analytically, i.e., without computer simulation, by arranging the circles in a curved hexagonal packing pattern including six curved paths of circles.

FIG. 3A illustrates a curved hexagonal packing pattern 300 obtained for the hexagonal number of 61 circles or discs 310 of equal sizes by use of the analytical method for obtaining a dense circular pattern. The pattern shows the six curved paths 301 (illustrated by hatched circles) of adjacent circles extending from the center of the circumscribed circle 311 (outer circular boundary 311) to the periphery of the circumscribed circle.

In general, the lenslets of a light collector according to the analytical method, are arranged in six curved paths of adjacent lenslets, wherein each path extends from the center of the light collector to the outer circular boundary and wherein consecutive straight lines starting from a lenslet located adjacent to a lenslet located at the center of the light collector and ending at the outer circular boundary are angled with respect to the preceding straight line by an angle αk=+/−pi/3k, where k defines the number of adjacent lenslets in each of the curved paths with the exclusion of the lenslet located at the center of the light collector.

The inventor has recognized that the methods described in references (1), (2) and (3) can be used in the process of developing a light collector.

The dense pattern 300 or other patterns of a hexagonal or non-hexagonal number of densely packed discs contained within a circular boundary 311 is utilized in an embodiment of the invention for placing the lenslets 121 in a dense pattern. Accordingly, the discs 310 can be replaced by lenslets so that a circle or disc 310 and the area of a disc 310 are equivalent to a circumference of a lenslet and an area of that circumference. The circumference of a lenslet may be defined by the footprint of the lenslet, i.e., the circumference of the entrance or exit surface of a lenslet. Thus, a lenslet 121 as depicted in FIG. 1B may correspond to a cross-section of a lenslet or a footprint of a lenslet so that the footprint of lenslet 121 is equivalent to a circle 310. Therefore, the circles 310 and the outer circular boundary 311 also represent cross sectional views or footprints of lenslets 121 and an outer circular boundary 180, respectively. For convenience, the reference number 310 will be used for referring to lenslets 121 and the outer circular boundary 311 will be used for referring to the outer circular boundary 180 of the lenslets.

Thus, each lenslet defines a disc 310 corresponding to a substantially circular cross section of the lenslet 121. It is understood that the substantially circular cross section need not be exactly circular but may be circular in a broader sense which includes elliptical or other shapes. The possible deviation from an exact circular shape is due to the merging of lenslets by extending the volume of lenslets (described elsewhere herein). Furthermore, the discs 310 of the lenslets 121 have the same diameter and are located in a common plane which is perpendicular to the optical axis 150. Further, the dense pattern of the lenslets has been obtained by optimizing a packaging density defined by a ratio of a sum of areas of the discs 310 and an area of a container disc 311 circumscribing the discs 310.

It is noted that the shape of a cross section of lenslets 121 in a plane substantially perpendicular to the optical axis of the lenslet is non-hexagonal, i.e., does not include hexagonal shapes, but may include circular shapes or deviations of circular shaped which have a smooth circumference.

Accordingly, as illustrated in FIG. 1B, the lenslets 121 of a light collector 120 may comprise a plurality of outermost adjacent lenslets located along an outer circular boundary 180, wherein each of the outermost lenslets has the same radial distance 170 to a center of the light collector, and wherein the dense pattern has been obtained by optimizing a packaging density defined by a ratio of a sum of areas of the circular cross sections or footprints of the lenslets 121 and an area of the outer circular boundary 180.

In the case that the light collector 120 is configured with a hexagonal number of lenslets 121, the dense pattern of lenslets can be analytically determined as shown in FIG. 3A and as described in references (1) and (2), by determining a pattern which includes six curved paths 301 of adjacent lenslets 310, wherein each path extend from the center of the light collector 120 to the outer circular boundary 311.

As illustrated in FIG. 3A, each curved path 301 may be determined by initially defining an number of straight lines 318a-318d, which connects centers of the adjacent lenses and by determining angles αk between the straight lines, so that the consecutive straight lines starting from a lenslet located adjacent to the lenslet located at the center of the light collector 120 and ending at the outer circular boundary 311 are angled with respect to the preceding straight line by an angle α_k=π/3k where k is the hex-number and is given by eq. 1 and defines the number of adjacent lenslets in a curved path (shown by hatched circles) with exclusion of the lenslet located at the center of the light collector.

It is characteristic that the curved paths (illustrated by the hatched circles) are invariant under a 60 degrees rotation and consequently that the dense pattern of all lenslets comprised by a light collector 120 is invariant under a 60 degrees rotation.

In the illustrated embodiment, constructive straight lines have been angled in the clockwise direction, however it is noticed that they also can be angled in the counterclockwise direction resulting in a mirrored pattern. The curved hexagonal pattern comprises a number of layers/rings which have been labeled by numbers 0-4 where the layers and rings can be defined and arranged as describe in connection with FIG. 1B.

Further, a number of permutations of the curved hexagonal patterns exist and these permutations can be obtained by rotating sets of constructive layers starting from the 2nd layer and out by an angle corresponding to αk in the opposite directing as in the basic curved regular patterns as illustrated in FIG. 3A. Rotating constructive layers means that all layers outside innermost rotated layer (the first layer to be rotated) are rotated by the same angle and in the same direction. For instance, in general with layer 2 as the inner most rotated layer would result in that all layers 2 to k are rotated and with layer 3 as the innermost layer would result in the fact that all layers 3 to k are rotated. It is noticed that it does not matter whether or not the outermost layer k is rotated as this layer is invariant under rotations of αk. As a consequence there exit k–3 (rotation of layer 0, 1 and K does not result in permutations) different ways that the constructive outer layers can be rotated in relation to the innermost non-rotated layers. In addition, it is noticed that mirror permutations of the different patterns also exists.

FIG. 3B illustrates a permutation of the basic pattern of FIG. 3A, where layers 2, 3 and 4 have been rotated αk degrees in the counter clockwise direction in relation to layer 0 and 1. Arrows 320a, 320b, 320c indicate respectively, the rotation of 2nd, 3rd and 4th layer.

FIG. 3C illustrates a permutation of the basic pattern where layers 3 and 4 have been rotated αk degrees in the counter clockwise direction in relation to layer 0, 1, 3. Arrows 320b, 320c indicate respectively the rotation of 3rd and 4th layer.

The dense circular pattern of the lenslets, where a plurality of outermost adjacent lenslets are located along an outer circular boundary, wherein each of the outermost lenslets has the same radial distance to a center of the light collector, can thus for a hexagon number (defined by equation 1) both analytically or through iterative analysis/calculations, for example, performed by a computer. The dense circular pattern of a non-hexagon number of lenslets can be found through iterative analysis/calculations. FIG. 4A-4L illustrate a number of dense circular patterns of lenslets and which have be created through computer simulations.

Whether the light collector 120 is configured with a hexagonal or non-hexagonal number of lenslets 121, it is characteristic that at least some of the outermost lenslets, i.e., lenslets in the outermost ring 181, are located adjacent to two other outermost located lenslets. In the case that the light collector 120 is configured with a hexagonal number of lenslets it is characteristic that each of the outermost lenslets are located adjacent to and in contact with two other outermost located lenslets, i.e., the outermost lenslets forms a closed ring outer 181.

The number of lenslets 121 in a light collector 120 may be larger than 14. In order to obtain a large packaging density, the number of lenslets may be chosen according to eq. 1 with k greater than two. Alternatively, the number of

lenslets may be chosen to be a non-hexagonal number, but chosen according to the equation for a reduced hexagonal number hr(k):

$$hr(k)=3k(k+1), \text{ wherein } k \text{ is an integer} \qquad \text{(Eq. 2)}$$

Thus, the number of lenslets given by eq. 2 is one less than the hexagonal numbers given by eq. 1. The packaging density which is obtainable by designing a light collector with a number of lenslets given by eq. 2 is close to the packaging density obtainable by designing a light collector with a number of lenslets given by eq. 1. Further, in some embodiments the dense circular pattern can be made based on a hexagonal number of lenslets. However, one of the lenslets have be removed in order to use its space for other purposes for instance as inlet space for molding material during the molding process. The number of lenslets is thus reduced to a number given by equation 2.

FIGS. 12A, 12B and 12C illustrate graphs of the packing density of circular lenslets packed in a circle and comprising at least 7 outermost lenslets as a function of the number of lenslets. The packing densities of the circular lenslets packed in a circle have been obtained based on a number of dense circular packaging of circular lenslets obtained by computer simulations. FIG. 12A illustrates the packing density in the interval 1-225 lenslets; FIG. 12B illustrates the packing density in the interval 200-700 lenslets; and FIG. 12C illustrates the packing density in the interval 700-1500 lenslets. The horizontal axis 1280 indicates the number of lenslets and the vertical axis 1281 indicates the packing density of the circular lenslets inside the circle defined by the area of the outer circular boundary defined by the outermost lenslets. The line 1282 indicates the graph of the packing density.

The graphs reveal that there are a number of local crowning intervals I1-I25, where the packaging densities of the lenslets are higher than the surrounding ranges of number of lenslets. In one embodiment, the light collector according the present invention comprises a number of lenslets within one of the crowing intervals I1-I25 indicated in table 0a, where the crowing intervals I1-I25 are indicated as closed intervals meaning that the end points indicated in table 0a are included in the crowing intervals I1-I25.

TABLE 0a

Intervals with higher circular packaging density than surroundings ranges of number of lenslets

Interval number	Number of lenslets	
	Start	End
I1	18	21
I2	36	38
I3	54	55
I4	60	61
I5	82	87
I6	113	122
I7	148	157
I8	198	201
I9	234	254
I10	264	276
I11	291	302
I12	327	337
I13	498	425
I14	478	501
I15	560	583
I16	630	660
I17	718	747
I18	779	789
I19	817	847

TABLE 0a-continued

Intervals with higher circular packaging density than surroundings ranges of number of lenslets		
Interval	Number of lenslets	
number	Start	End
I20	910	913
I21	927	933
I22	1124	1138
I23	1231	1244
I24	1415	1446
I25	1468	1500

Choosing the number of lenslets to be in one of the crowing intervals I1-I25 ensures that the packaging density of lenslets can be optimized within a given range of lenslets. For instance, if due to other reasons the number of light sources must be within the range of 50-75 light sources, it can be seen that the number of lenslets and light sources can be chosen from crowing intervals I3 and I4 in order to optimize the packaging density of the lenslets and thereby also optimize the efficiency of the illumination device. Similarly, if the number of light sources must be within the range of 75-125 numbers of light sources, then the number of lenslets and light sources can be chosen from crowing intervals I5 and I6.

Further, the graphs show that there are a number of local density peaks P1-P51, where the packaging density with a specific number of lenslets are higher that the density of the surrounding number of lenslets.

It can be seen that for a total number of lenslets that are less than 100 that the at the number of lenslets equal the a hexagonal numbers given in equation 1 forms local density peaks P2, P4, and P6. However, surprisingly it is also apparent that if the number of lenslets equals a hexagonal number minus 6 also form substantial density peaks, for instance P3, P5 and P7.

In one embodiment the light collector according the present invention comprises a number of lenslets equal to one of the local density peaks as indicated in table 0b.

TABLE 0b

Density peaks with higher density packaging than surrounding number of lenslets		
Peak number	Number of lenslets	Packaging density
P1	19	0.8032
P2	37	0.8100
P3	55	0.8158
P4	61	0.8131
P5	85	0.8229
P6	91	0.8150
P7	121	0.8231
P8	151	0.8315
P9	199	0.8388
P10	219	0.8377
P11	235	0.8414
P12	241	0.8423
P13	270	0.8439
P14	295	0.8477
P15	301	0.8477
P16	331	0.8476
P17	349	0.8518
P18	421	0.8589
P19	481	0.8603
P20	499	0.8618
P21	528	0.8589
P22	565	0.8638

TABLE 0b-continued

Density peaks with higher density packaging than surrounding number of lenslets		
Peak number	Number of lenslets	Packaging density
P23	631	0.8632
P24	637	0.8636
P25	649	0.8641
P26	690	0.8648
P27	745	0.8668
P28	783	0.8672
P29	847	0.8689
P30	913	0.8707
P31	931	0.8701
P32	1003	0.8685
P33	1015	0.8708
P34	1027	0.8715
P35	1039	0.8703
P36	1045	0.8708
P37	1092	0.8704
P38	1133	0.8713
P39	1180	0.8705
P40	1201	0.8707
P42	1236	0.8711
P43	1244	0.8711
P44	1278	0.8712
P45	1304	0.8722
P46	1379	0.8719
P47	1420	0.8733
P48	1427	0.8733
P49	1436	0.8735
P50	1446	0.8732
P51	1491	0.8752

By designing the light collector with a number of lenslets at the local density peaks P1-P51 it possible to within a given range of number of light sources and lenslets to design the light collector with the densest lenslets pattern and thereby optimize the light output. For instance, if due to other reasons, the number of light sources must be within the range of 50-75 light sources, it can be seen that the number of lenslets and light sources can be from the following peak local density peaks P3 and P4 in order to optimize the packaging density of the lenslets and thereby also optimize the efficiency of the illumination device. Similarly, if the number of light sources must be within the range of 75-125 numbers of light sources, then the number of lenslets and light sources can be chosen from the local density peaks P5, P6 or P7. It can be seen that the crowing intervals and local density peaks tend to be less dominant as the number of lenslets increases; however, improvements in efficiency can still be achieved by choosing the number of lenslets at the peak density points and/or with in the peak density intervals.

The packaging density as defined above generally increases for increasing numbers of lenslets. Thus, for dense packing, the packaging density varies between approximately 0.71 for a light collector with 15 lenslets and approximately 0.88 for a light collector with 1500 lenslets. The packaging densities at the local density peaks P1-P51 are indicated in table 0b.

FIGS. 4A-4G illustrate a number of exemplary dense circular packagings of circular lenslets 421 obtainable by computer simulations. The lenslets have been arranged in a circle with a radius of 1 (one). The resulting radiuses of the lenslets and the packing density have been indicated below. The coordinates of the center of the lenslets 421 in relation to the center of the circle have been indicated in the tables at the end of this application. The person skilled in the art would be able to scale the size of the circumscribed circle into any desired size and scale the size and coordinates of the

lenslets accordingly. That is, if a diameter of the circumscribed circle should be 10 (in a given unit) then the radius of the lenslets and the radial part of the coordinates should be multiplied by 10.

FIG. 4A illustrates a dense circular packaging of 15 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.2212 and the packaging density of the lenslets is 0.7338.

FIG. 4B illustrates a dense circular packaging of 24 circular lenslets 421 that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.1693 and the packaging density of the lenslets is 0.7740.

FIG. 4C illustrates a dense circular packaging of 36 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.1482 and the packaging density of the lenslets is 0.7909. Thus, in one embodiment, the illumination device according to the present invention comprises at least 36 lenslets and has a packaging density of at least 0.79.

FIG. 4D illustrates a dense circular packaging of 37 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.1480 and the packaging density of the lenslets is 0.8100. This packaging corresponds to a local density point P2 and is within the crowing interval I2. Thus, in one embodiment the illumination device according to the present invention comprises at least 37 lenslets and has a packaging density of at least 0.81.

FIG. 4E illustrates a dense circular packaging of 60 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.1157 and the packaging density of the lenslets is 0.8026. This packaging is within the crowing interval I4. Thus, in one embodiment the illumination device according to the present invention comprises at least 60 lenslets and has a packaging density of at least 0.80.

FIG. 4F illustrates a dense circular packaging of 61 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.1155 and the packaging density of the lenslets is 0.8131. This packaging corresponds to local density point P4 and is within the crowing interval I4. Thus, in one embodiment the illumination device according to the present invention comprises at least 61 lenslets and has a packaging density of at least 0.81.

FIG. 4G illustrates a dense circular packaging of 90 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.0948 and the packaging density of the lenslets is 0.8092. Thus, in one embodiment the illumination device according the the present invention comprises at least 90 lenslets and has a packaging density of at least 0.80.

FIG. 4H illustrates a dense circular packaging of 91 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.0946 and the packaging density of the lenslets is 0.8150. This packaging corresponds to local density point P6.

FIG. 4I illustrates a dense circular packaging of 121 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.0825 and the packaging density of the lenslets is 0.8231. This packaging corresponds to a local density point P7 and is within the crowing interval I6.

FIG. 4J illustrates a dense circular packaging of 151 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.10742 and the packaging density of the lenslets is 0.8315. This packaging corresponds to a local density point P8 and is within the crowing interval I7.

FIG. 4K illustrates a dense circular packaging of 199 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.0649 and the packaging density of the lenslets is 0.8388. This packaging corresponds to a local density point P9 and is within the crowing interval I7.

FIG. 4L illustrates a dense circular packaging of 235 circular lenslets that are arranged in a dense circular pattern. The relative radius of the lenslets in relation to the outer circular boundary of the circular pattern is 0.0598 and the packaging density of the lenslets is 0.8414. This packaging corresponds to a local density point P11 and is within the crowing interval I9.

FIG. 4E illustrates a light collector 120 with 60 lenslets as given by eq. 2 with k=4. An alternative design with 60 lenslets can be provided by providing a light collector 120 with 61 lenslets as shown in FIG. 4F where one lenslet has been removed, for example, where the center lens or a lens located along the circumscribing circle has been removed. The packing density for a light collector 120 with 61 lenslets as shown in FIG. 4E is 0.8131 and the packing density for a light collector with 60 lenslets provide by removing one lenslet from the light collector with 61 lenslets is 0.8000. The packing density of the optimized 60 packing (FIG. 4E) provides 0.8026. On the other hand, a light collector with 62 lenslets only has a packaging density of 0.795. Similar the packing density for a light collector 120 with 91 lenslets as illustrated in FIG. 4H is 0.8150 and the packing density for a light collector 120 with 90 lenslets provide by removing one lenslet from the light collector with 91 lenslets is 0.8060. The packing density of the optimized 90 packing (FIG. 4G) provides 0.8092. On the other hand, a light collector 120 with 92 lenslets only has a packaging density of 0.8058. Accordingly, light collectors 120 with a hexagonal number of lenslets tends to have higher packaging densities, light collectors 120 with a reduced hexagonal number of lenslets according to Eq. 2 has slightly reduced packaging densities whereas light collectors with an increased hexagonal number of lenslets (i.e., the number provided by Eq. 1 added with one) has significantly reduced packaging densities. Accordingly, light collectors 120 having a number of lenslets as provided by Eq. 1 or Eq. 2 may be preferred.

The light collectors in FIGS. 4D, 4F and 4H, respectively, having 37, 61 and 91 lenslets contains a hexagonal number of lenslets according to Eq. 1, whereas light collectors having in FIGS. 4C, 4F and 4G respectively, 36, 60 and 90 lenslets contains a reduced hexagonal number of lenslets according to Eq. 2. Any of the light collector designs with a hexagonal number of lenslets can be modified to a design with a reduced hexagonal number of lenslets by removing one lenslets. Removal of one lenslet from a design with a hexagonal number of lenslets may be necessary in order to establish hole in a mold for the light collector wherein molding material can be injected. However, other number of lenslets may also be used, for instance as illustrated in FIGS. 4B, 4I, 4J, 4K and 4L where the light collectors respectively

have 27, 121, 151, 199 and 235 lenslets, and which has been chosen as the density of the lenslets in these embodiments forms a local maximum compared the density of light collects having a similar but different number of lenslets. For instance, the light collector in FIG. 4B with 27 lenslets from a local density maximum (0.7740) as it has a higher density than a light collector with 26 (0.7654) and 28 (0.7739) lenslets. Further, the light collectors illustrated in FIGS. 4I, 4J, 4K, 4L respectively with 121, 151, 199, 235 all form a local density maximum with a density larger than the density of light collectors having between –5 and +5 lenslets. The same is the case with light collectors having 19, 37, 55, 61, 85, 91, 100, 135, 151, 176, 219, 235, 241, 253 lenslets, however it is noticed that light collectors with others larger number of lenslets also may fulfill this. Also, the light collectors with 19, 37, 55, 85, 121, 151, 199, 219, 241 and 270 all forms a local density maximum with a density larger than the density of light collectors having between –10 and +10 lenslets.

The number of lenslets can also be chosen based on power and cooling requirements of the LED light engine system and then optimized to a dense circular pattern. For instance, the light collectors illustrated in FIG. 4A comprises 15 lenslets which is useful in connection with 15 diodes of the type SBT-70 LED's from luminous devices as the power and driver requirements fits with 0.6 kW which fits with the number of drivers and power supply of an existing product from the applicant. The number of lenslets can thus be chosen based on other requirements in addition to the pure optical requirements.

Tables 1a-11 in the end of the detailed description show normalized coordinates for the placement of lenslets of the light collectors in FIGS. 4A-L.

According to the embodiments, the lenslets may comprise a plurality of outermost adjacent lenslets located along an outer circular boundary 180. Accordingly, the densely packed lenslets form a light collector having a circular periphery. The circular light collector is in contrast to hexagonal shaped light collectors, i.e., light collectors having a hexagonal periphery or hexagonal entrance and exit apertures. Such hexagonal light collectors may be chosen to obtain a high packaging density, possibly a packaging density of 0.907 for a hexagonal pattern of lenslets. A disadvantage of hexagonal light collectors is the non-circular periphery. For example, the non-circular periphery of a hexagonal light collector may be disadvantageous since there is a mis-match between the non-circular pattern of the light collector and the round pupil of the imaging system. This leads to pure efficiency and bad image/light quality. Advantageously, embodiments of the present invention may achieve both a circular periphery and a high packaging density by use of a non-hexagonal packaging pattern, i.e., a curved hexagonal packaging pattern.

FIGS. 5-8 illustrate another aspect of the light collector according to the present invention and illustrate the manner in which the lenslets can be joined with a reduced amount of "dead" areas/zones of the light collector.

FIGS. 5A-5E illustrate cross sectional views of adjacent lenslets 521a-521c of a light collector 520.

FIG. 5A illustrate a principal illustration of a number of adjacent lenslets 521a, 521b, 521c in a light collector 520. The adjacent or adjoining lenslets may have different radial distances 170 (illustrated in FIG. 1B) to the center of the light collector 120 or to the optical axis 150. The adjacent lenslets 521a, 521b, 521c have different longitudinal or axial positions along the optical axis 150, i.e., so that the axial distances 201 (illustrated in FIG. 2A) between the lenslets

and light sources (not shown in FIG. 5A) along the optical axis for the adjacent lenslets 521a, 521b, 521c are different. The footprint of the lenslets 521a, 521b, 521c, i.e., the largest cross sectional area in a plane perpendicular to the optical axis 150, e.g., the area of the largest circular periphery are indicated by reference 511a, 511b or 511c.

In an embodiment, the light collector 520 is molded as a one piece light collector so that the assembly of all lenslets 521 is integrally formed as a single piece. In such a molded light collector 520, it would be possible to connect the adjacent lenslets 521a-521c, e.g., by adding material in a volume as indicated by reference 519a, 519b. However, such a connection volume 519a, 519b may be undesirable since the connection volume 519a, 519b may introduce steep edges which may not be acceptable due to molding requirements, for example, since the edges may make it impossible to separate the molded light collector from the mold. The connection volume 519a, 519b may also be undesirable since the resulting assembly of lenslets may not utilize the light collecting property of the light collector 120 in a sufficient way.

In order to improve molding conditions and to improve the percentage of power of emitted light from the light sources 111 which is transmitted through the gate 130, the adjacent lenslets 521a-c may be connected by extending the volume of one or all of the adjacent lenslets 521a-c.

FIG. 5B shows the lenslets 521a-521c from FIG. 5A in an unconnected configuration. FIG. 5B shows a separation 523a and 523b respectively, between the lenslets 521a/521b and 521b/521c for convenience. However, it is noted that at least some or most of the adjacent lenslets connect at a point due to the dense packing as shown, for example, in FIG. 1B.

FIG. 5C illustrates the manner in which a volume of a lenslets 521a, 521b, 521c are extended by extending the upper curved exit surface 551b (for simplicity only indicated for lenslet 521b) and the lower curved entrance surface 553b beyond the plane edges 555b until the surfaces meet at a point 557b as indicated by broken lines. The surfaces are extended along the mathematically defined three-dimensional surfaces (typical determined by an optical design program) of the lenslets.

As can be seen in FIG. 5C, the extension or growth of the lenslet surfaces may not cause the lenslets to grown into each other. FIG. 5D illustrates that in order to connect adjacent lenslets, which does not merge by extending the exit and entrance surfaces, additional connection volumes 559 (hatched areas) are introduced between the extended adjacent lenslets. The additional connection volumes 559 are introduced by extending the entrance surface 553a of a first of the adjacent lenses and the exit surface 551b of a second of the adjacent lenses until they meet at a common point 561. The additional volume 559 is then added above the extended parts of the entrance surface 553a and the exit surface 551b of the adjacent lenses. The top of the additional volume is provided between the exit surfaces 551a and 551b of the adjacent lenslets and the height of the additional volume depends on molding and strength requirements to the light collector, as in order to allow molding the thickness of the light collector need to be above a certain dimension in order to allow flow of the molding material and the strengthen the light collector does also depend the thickness.

FIG. 5E illustrates a cross section of the final light collector shown in FIGS. 5B-5D. Merging the lenslets as described above make it possible to minimize the additional volumes and maintain more of the original optical properties of the lenslets, as a result more light can be collected and directed in the desired direction.

FIG. **6A-6C** illustrate cross sectional views of adjacent lenslets **621a**, **621b** of a light collector and illustrate principles for making extended lenslets **621** when the lenslet surfaces are grown into each other.

FIG. **6A** shows the lenslets **621a** and **621b** in an unconnected configuration. FIG. **6A** shows a separation **623** between the lenslets **621a/621b** for convenience. However, it is noted that at least some or most of the adjacent lenslets connect at a point due to the dense packing as shown in, for example, FIG. **1B**.

FIG. **6B** illustrates the manner in which a volume of the lenslet **621b** is extended by extending the upper curved exit surface **651b** and the lower curved entrance surface **653b** beyond the plane edges **655b** until the surfaces meet at a point **657b** as indicated by broken lines. The surfaces are extended along the mathematically defined three-dimensional surfaces of the lenslets. In this embodiment, the lenslets **621a** and **621b** are arranged so close that lenslet **621a** will grow into lenslet **621** when the entrance surface **653b** and exit surface **655b** are extended until they meet in point **657b**. In this situation, the entrance surface **653b** and exit surface **655b** are extended until they the meet the adjacent surfaces of lenslet **621a**. The resulting light collector **620** is shown in FIG. **6C**.

FIG. **7A-7D** illustrate cross sectional views of adjacent lenslets **721a**, **721b** of a light collector **720** and illustrate principles for making extended lenslets **721** when the two adjacent lenslets grow into each other when both lenslets are grown.

FIG. **7A** illustrate the lenslets **721a** and **721b** in an unconnected configuration. FIG. **7A** shows a separation **723** between the lenslets **721a/721b** for convenience.

FIGS. **7B** and **7C** illustrate the manner in which the volume of the lenslets **721a** and **721b** are extended by extending the upper curved exit surfaces **751a**, **751b** and the lower curved entrance surfaces **753a**,**753b** beyond the edges **755a** and **755b** until they, respectively, meet in points **757a**, **757b** as indicated by broken lines. The surfaces are extended along the mathematically defined three-dimensional surfaces of the lenslets. In this embodiment, the extended exit surfaces **751a** and **751b** meet in point **759** and the exit surfaces **751a** and **751b** are only extended to this point and the two lenslets are thus joined in this point. At the entrance side, hatched part **761** has a structure which cannot be molded since slip-angles of the extended surface **751a** at the entrance side are smaller than an allowed minimum slip angle (e.g., 91 degrees). Furthermore, the parts **761** contain lens volumes which have no optical effect or has undesired optical effects. Removal of the volume **761** further has the effect that the area of the entrance surface of lenslet **721b** is increased since the shadow effect of part **761** on lenslet **721b** is removed. Correspondingly, the shadow of part **761** on the lenslet **721a** for a light propagating along the optical axis **150** is eliminated by removal of part **761** and, thereby, part **761**.

The resulting design is shown in FIG. **7D** wherein the angles of edges are larger than the allowed minimum slip angle. The design in FIG. **7D** also satisfies the requirements to the minimum thickness of the material of the light collector.

FIGS. **8A-8H** illustrate the manner in which the volume of a number of lenslets **821a**, **821b**, **821c** are extended by extending the upper curved exit surfaces and the lower curved entrance surfaces and further illustrate the manner in which the lenslets can be extended at different cross sections of the light collector. FIGS. **8A-8D** illustrate the light collector **820** in an un-grown configuration prior to letting

the lenslets grow and FIGS. **8E-8H** illustrates the light collector **820** in a grown configuration, where the lenslets have grown into each other. FIGS. **8A** and **8E** illustrate a top view of the light collector. FIGS. **8B** and **8F** illustrates a cross sectional view respectively along line A-A in FIG. **8A** and line A'-A' in **8E**; FIGS. **8C** and **8G** illustrates a cross sectional view respectively along line B-B in FIG. **8A** and line B'-B' in **8E**; FIGS. **8D** and **8H** illustrates a cross sectional view respectively along line C-C in FIG. **8A** and line C'-C' in **8E**.

In the cross sectional view of the un-grown light collector **820** in FIG. **8B-8D**, the dotted lines indicates the extended parts of the entrance and exit surfaces of the lenslets **821a**, **821b**, **821 c** and in the top view, the dotted lines indicate where the extended exit surface and extended exit surface of each lenslets will meet if they are extended until they meet.

In FIGS. **8B** and **8F**, it can be seen that the lenslets already meet (due to dense packaging described above) a long line C-C and C'-C' and it is thus not necessary to grow the lenslets into each at these points. The lenslets **821a** and **821c** have thus only been grown at the outermost part along line C-C and C'-C' the lenslets are not grown at the points where the lenslets meet.

In FIGS. **8C** and **8G** it can be seen that along line B-B and B'-B', the exit surface of lenslet **821a** and **821b** have been extended until the meet in a point between the two lenslets and the their entrance surface also have been extended until they meet in a point between the two lenslets. It can also be seen that extended exit surface of lenslet **821c** hits/meets the exit surface of lenslets **821b** and that the extended exit surface of lenslet **821c** hits/meets the entrance surface of lenslets **821b**. As a result, along line B-B and B'-B', only the lenslet **821c** have been grown until it meets the original lenslet **821b**. As can been seen in the top view illustrated in FIG. **8E** the result is that a part of the boundary **861** (curved part) where lenslets **821b** and **821c** meet follows the original shape of lenslet **821b**.

In FIGS. **8D** and **8H**, it can be seen that along line A-A and A'-A' that the extension of the exit surface and entrance surface of lenslets **821a** and **821b** does not result in the lenslets being merged. An additional volume **859** has been added an additional volume (as describe in FIG. **5**) in the area between the extended lenslets and such that the minimum thickness requirements are fulfilled. Further, it can be seen that along line A-A and A'-A' that the exit surface of lenslet **821b** and **821c** have been extended until the meet in point between the two lenslets and that the their entrance surface also have been extended until they meet in a point between the two lenslets.

FIGS. **8A-8H** illustrate a row of three lenslets however it is to be understood that any number of lenslets can be grown into each other and that the lenslets can be arranged in array having any shape.

FIGS. **9A-9C** illustrate an illumination device in the form of a gobo projector **900** comprising a light source module **901**. The light source module **901** comprises a light collector **920** and a light unit **910** similar to the one depicted in FIG. **1**. FIG. **9A** illustrates a front perspective view of the illumination device, FIG. **9B** illustrates a cross sectional view, and FIG. **9C** illustrates an enlarged cross sectional view of the light source module **901**, light collector **920**, light unit **910** and a gobo wheel **913**. The illumination device further comprises a projecting system **905** adapted to image the gobo of one of the apertures **903** onto a target surface.

The gobo wheel **913** comprising a number of gobos **915** mounted on a rotating carousel as known in the art of entertainment lighting. The gobo wheel can for instance be

embodied as described in U.S. Pat. Nos. 5,402,326, 6,601,973, 6,687,063 or U.S. Publication No. 2009/0122548 incorporated herein by reference. Each gobo can be moved into aperture **903** by rotating the carousel. The aperture **903** is equivalent to the gate **130** shown in FIG. **1**.

The projecting system is adapted to create an image of the gobo at a target surface (not shown) and comprises a projecting system **905** including a number of optical lenses, such as, for instance, a front lens **919**, a number of zoom lenses **921**, and a number of focus lenses **923**. The zoom lenses and focus lenses can be moved in relation the front lens and the aperture, as known in the art of projecting systems.

The illustrated gobo projector can also comprise a color wheel comprising a number of optical filters (e.g., dichroic filters, color gels or the like) which can also be positioned into the light beam. The color wheel is useful in the case that the light sources produce a white light beam and can be used to create a certain color of the light beam. Graduated color filters which gradually can change the color of the light beam can also be used, for instance in connection with the known CMY color mixing systems. The color wheel is, however, optional, as it can be omitted in the case where the light sources **111** are of different colors and adapted to perform additive color mixing as known in the art of dynamic lighting. This is for instance possible by having a number of red, green and blue LEDs where the color mixing is based on the intensity of the different colors. The intensity of the different colors can for instance be controlled by the commonly known pulse width modulation (PWM) method, or by adjusting the DC current through each color LED.

FIG. **9C** shows that lenslets have different axial distances (illustrated in FIG. **2A**) between an arbitrary plane of the light unit **910** where the light sources are placed. FIG. **9C** also shows the different angling of lenslets **921** (as also shown in FIG. **2C**) relative to the optical axis **150**. The lenslets **921** also have different optical powers which however may be difficult to see clearly from FIG. **9C**.

FIGS. **10A-10E** illustrate views of a light collector **1020** with 90 lenslets **1021**, where FIG. **10A** is a top view (seen towards the exit surfaces of the lenslets); FIG. **10B** is a cross sectional view along line II-II; FIG. **10C** is a tilted view of exit surface of the light collector FIG. **10d** is a side view of the light collector **1020**; and FIG. **10E** is a tilted view of entrance surface of the light collector.

The 90 lenslets **1021** of the light collector **1020** are arranged in a dense circular packaging as described previously. The dense circular packaging is equivalent to the circular packing shown in FIG. **4H**, and where the center lens have been omitted in order to use this space as a molding inlet.

The top image illustrates that the extended lenslets (i.e., lenslets extended according to the principles described in connection with FIG. **5-8**) are merged together so that the exit surfaces of adjacent lenslets meet along boundaries or edges **1040** (only a few are indicated by a labeled in the figure). The boundary **1040** between at least some of the adjacent lenslets may have a length greater than 1 mm or greater than at least 5% of the diameter of a lenslet or even greater than 20% of the diameter of a lenslet as shown in the drawings.

FIG. **10B** illustrates that the lenslets **1021** have different longitudinal/axial positions and/or have optical axes **1050** that are angled relative to the optical axis **150** of the light collector.

Further, the dense pattern includes plane zones **1010** having plane or substantially plane surfaces of a given area

of substantial size. The plane surfaces may be substantially perpendicular or angled in relation to the optical axis **150**. The front and back faces of the plane zones are respectively denoted as exit and entrance surfaces in analogy with the exit and entrance surfaces of the lenslets. Thus, the plane zones have no optical power. Due to molding requirements, the thickness of the plane zones along the optical axis **150** is at least 2 mm, or at least 3 mm, however, silicone based light collectors can be molded with thickness of at least 1 mm. The FIGS. **10A** and **10B** show that exit surfaces **1020** of at least some of the lenslets **1021** meet the exit surfaces of the plane zones **1010** along a curved boundary **1041**.

Advantageously, some of the plane zones **1010** in the light collector may comprise mounting holes **1024**, for example, for mounting the light collector fixedly relative to the light collector **120**. The planar zones may also be provided with bosses/turrets **1026** adapted to support the light collector when mounted. Further, a number of protrusions **1028** may be provided at the outer part of the light collector and these protrusions may be provided with holes and/or supporting means for fastening the light collector to a PCB with the LEDs.

FIG. **10B** illustrates that the light collector **120** comprises a front side **1031** on which all exit surfaces **1020** are located and a back side **1032** on which all entrance surfaces **1033** are located.

In order to provide an inlet for enabling the liquid molding material to flow into the mold, the mold may be configured so that the resulting dense pattern of lenslets of the light collector does not include a lenslet at the center of the light collector or so that a lenslet at another location has been removed. FIG. **10A** shows that the light collector does not have a lenslet in the center **1099**. In general a light collector **1020** may be configured so that at least one of the lenslets in the dense pattern is omitted in order to enable molding of the light collector.

FIGS. **11A-11F** illustrate views of a light collector **1120** with 15 lenslets **1121**, where FIG. **11a** is a top view, FIG. **11B** is a cross sectional view along line IV-IV, FIG. **11C** is a cross sectional view along line V-V; FIG. **11D** is a top perspective view, FIG. **11E** is a side view and FIG. **11f** is a bottom perspective view. The reference signs in FIGS. **11A-11F** refer to features which are identical or equivalent to features indicated with the same reference signs in FIGS. **10A-10F** and will not be described further.

The dense circular packaging is equivalent to the circular packing shown in FIG. **4A** with 15 lenslets and does thus not include a center lenslet—accordingly, the center **1112** in this design may be used for forming an inlet in the mold for the liquid molding material.

An embodiment of the invention relates to a method for manufacturing an illumination device. The method includes a molding step wherein a mold for a light collector is provided. The mold is shaped to form a plurality of lenslets adapted to collect light from the light sources and adapted to convert the collected light into a plurality of light beams so that the light beams propagate along an optical axis. The mold is shaped so that each of the lenslets comprises an entrance surface where the light enters the lenslet and an exit surface where the light exits the lenslet, so that the lenslets are arranged in a dense circular pattern, and so that the axial distances between the lenslets and light sources along the optical axis for adjacent lenslets are different for at least some of the adjacent lenslets. The manufacturing method further comprises providing a light unit having a plurality of

light sources and arranging the light unit relative to the light collector so that lenslets are arranged at a correct position relative to the light sources.

A related embodiment of the invention relates to a method for manufacturing an illumination device wherein the method includes steps for determining a dense packing of the lenslets. The arrangement of the lenslets in a dense pattern comprises arranging a plurality of the lenslets as outermost lenslets along an outer circular boundary so that each of the outermost lenslets has the same radial distance to a center of the light collector. The method further comprises optimizing the packaging density of the lenslets by optimizing a packaging density defined by a ratio of a sum of areas of the circular cross sections or footprints of the lenslets and an area of the outer circular boundary.

A related embodiment of the invention relates to method for manufacturing a light collector adapted to collect light from a plurality of light sources wherein the method comprises:

   providing a mold of the light collector, wherein the mold is shaped to form a plurality of lenslets adapted to collect light from the light sources and adapted to convert the collected light into a plurality of light beams so that the light beams propagate along an optical axis, and wherein the mold is shaped so that:

   each of the lenslets comprises an entrance surface where said light enters the lenslet and an exit surface where the light exits the lenslet, and wherein

   the lenslets are arranged in a dense circular pattern including adjacent lenslets, wherein the exit surfaces of at least some pairs of the adjacent lenslets meet along a boundary.

Any of the methods for manufacturing a light collector may further include injecting a molding fluid into the mold through an inlet located in a center of the mold so that the center lenslet is missing in the molded light collector. Hereby is achieved that low tolerances in the light collector can be maintained as the flow and molding pressure of the molding material is symmetrical during the molding process. However low viscosity molding materials the mold could be injected through the edge so center lenslet could be maintained.

The present invention is described in view of an illumination device comprising a number of LEDs that generate a light beam. However the person skilled in the art realizes that any kind of light source such as discharge lamps, PLEDs, OLEDs, plasma sources, halogen sources, fluorescent light sources, and phosphor based light sources, etc. can be used. Further it is to be understood that the illustrated embodiments only serve as illustrating examples illustrating the principles of the present invention and that the skilled person will be able to provide several embodiments within the scope of the claims. In the illustrated embodiments the illustrated light beams and optical means do only serve as to illustrate the principles of the invention rather than illustrating exact and precise light beams and optical means. Any reference signs in the claims should not be construed as limiting the scope.

The following tables 1a-1l show normalized coordinates of lenslets of the light collector designs shown in FIGS. 4A-L respectively.

TABLE 1a

	15 lenslets density of lenslets 0.8388 radius of lenslets 0.0649	
x	y	distance to center
0.3579	0.1163	0.3763
0.0000	0.3763	0.3763
−0.3579	0.1163	0.3763
−0.2212	−0.3044	0.3763
0.2212	−0.3044	0.3763
0.6179	0.4741	0.7788
0.2600	0.7341	0.7788
−0.2600	0.7341	0.7788
−0.6179	0.4741	0.7788
−0.7786	−0.0204	0.7788
−0.6419	−0.4411	0.7788
−0.2212	−0.7468	0.7788
0.2212	−0.7468	0.7788
0.6419	−0.4411	0.7788
0.7786	−0.0204	0.7788

TABLE 1b

	24 lenslets density of lenslets 0.8414 radius of lenslets 0.0598	
x	y	distance to center
0.1560	−0.0559	0.1657
−0.1544	0.1141	0.1920
−0.0344	0.4634	0.4646
−0.3093	−0.3528	0.4692
0.3072	0.3572	0.4711
0.0233	−0.4735	0.4741
−0.4733	−0.0392	0.4749
0.3545	−0.3488	0.4973
0.4954	0.0444	0.4973
−0.3870	0.3808	0.5429
0.8164	−0.1045	0.8231
0.7848	0.2480	0.8231
−0.3717	0.7343	0.8231
−0.8229	0.0157	0.8231
−0.0290	0.8225	0.8231
−0.5447	−0.6171	0.8231
−0.7534	−0.3313	0.8231
0.3191	0.7587	0.8231
−0.2352	−0.7887	0.8231
0.6971	−0.4376	0.8231
0.1177	−0.8146	0.8231
0.6081	0.5546	0.8231
0.4489	−0.6899	0.8231
−0.7403	0.3598	0.8231

TABLE 1c

	36 lenslets density of lenslets 0.7908 radius of lenslets 0.0649	
x	y	distance to center
0.0006	0.0022	0.0023
−0.0611	−0.2877	0.2942
−0.2814	−0.0891	0.2952
0.2216	−0.1955	0.2955
−0.2172	0.2032	0.2975
0.2823	0.0947	0.2977
0.0644	0.2957	0.3026
0.4183	0.3639	0.5545
0.0773	−0.5499	0.5553
−0.4390	−0.3401	0.5553
−0.5136	0.2113	0.5553
0.5180	−0.2006	0.5555

TABLE 1c-continued

	36 lenslets density of lenslets 0.7908 radius of lenslets 0.0649	
x	y	distance to center
−0.2190	−0.5388	0.5816
0.3591	−0.4581	0.5821
−0.5776	−0.0781	0.5829
−0.3517	0.4674	0.5849
0.5787	0.0895	0.5856
0.1892	0.5646	0.5954
−0.1009	0.6254	0.6335
−0.3597	0.7712	0.8510
0.6579	0.5410	0.8518
−0.8107	−0.2613	0.8518
−0.4520	−0.7219	0.8518
0.4009	−0.7516	0.8518
−0.1772	−0.8331	0.8518
−0.6275	0.5760	0.8518
−0.6721	−0.5233	0.8518
0.6342	−0.5687	0.8518
0.7906	−0.3169	0.8518
−0.8510	0.0366	0.8518
0.4326	0.7337	0.8518
0.8035	0.2828	0.8518
0.0969	0.8463	0.8518
−0.7869	0.3260	0.8518
0.1190	−0.8434	0.8518
0.8514	−0.0267	0.8518

	37 lenslets density of lenslets 0.8414 radius of lenslets 0.0598	
x	y	distance to center
	Table 1l	
0.0000	0.0000	0.0000
0.2267	0.1902	0.2959
−0.2267	−0.1902	0.2959
−0.2781	0.1012	0.2959
0.2781	−0.1012	0.2959
−0.0514	0.2914	0.2959
0.0514	−0.2914	0.2959
0.0966	0.5477	0.5561
−0.0966	−0.5477	0.5561
−0.4260	0.3575	0.5561
0.4260	−0.3575	0.5561
0.5226	0.1902	0.5561
−0.5226	−0.1902	0.5561
0.3746	0.4465	0.5828
−0.1993	0.5477	0.5828
−0.3746	−0.4465	0.5828
0.1993	−0.5477	0.5828
−0.5740	0.1012	0.5828
0.5740	−0.1012	0.5828
0.4260	0.7379	0.8520
−0.4260	0.7379	0.8520
−0.4260	−0.7379	0.8520
0.4260	−0.7379	0.8520
0.6527	0.5477	0.8520
−0.6527	0.5477	0.8520
−0.6527	−0.5477	0.8520
0.6527	−0.5477	0.8520
0.8520	0.0000	0.8520
0.8007	0.2914	0.8520
−0.8007	0.2914	0.8520
−0.8520	0.0000	0.8520
−0.8007	−0.2914	0.8520
0.8007	−0.2914	0.8520
	Table 1d	
0.1480	0.8391	0.8520
−0.1480	0.8391	0.8520

-continued

	37 lenslets density of lenslets 0.8414 radius of lenslets 0.0598	
x	y	distance to center
−0.1480	−0.8391	0.8520
0.1480	−0.8391	0.8520

TABLE 1e

	60 lenslets density of lenslets 0.8388 radius of lenslets 0.0649	
x	y	distance to center
0.0010	0.0020	0.0023
−0.0764	−0.2160	0.2291
−0.2265	−0.0399	0.2300
0.1511	−0.1739	0.2304
−0.1458	0.1808	0.2323
0.2279	0.0466	0.2327
0.0811	0.2253	0.2395
−0.4143	0.0952	0.4251
−0.2854	−0.3160	0.4258
0.1329	−0.4045	0.4258
0.4173	−0.0863	0.4261
−0.1106	0.4125	0.4270
−0.0945	−0.4466	0.4565
−0.4352	−0.1397	0.4571
0.3417	−0.3049	0.4580
−0.3358	0.3128	0.4589
0.4353	0.1492	0.4601
0.1174	0.4538	0.4687
0.3255	0.3527	0.4800
−0.3652	0.5422	0.6537
0.6518	0.0679	0.6554
−0.6335	0.1691	0.6557
−0.2717	−0.5967	0.6557
0.1737	−0.6322	0.6557
−0.6529	−0.0614	0.6558
−0.4620	−0.4653	0.6558
0.3825	−0.5326	0.6558
0.6356	−0.1629	0.6561
−0.1557	0.6403	0.6589
−0.5550	0.3867	0.6764
−0.0537	−0.6743	0.6764
−0.6118	−0.2891	0.6767
0.5600	−0.3815	0.6776
0.6083	0.3026	0.6795
0.2933	0.6129	0.6795
0.0721	0.6806	0.6844
0.4985	0.5062	0.7105
0.2573	0.8440	0.8823
0.8827	0.0537	0.8843
0.8386	0.2807	0.8843
0.7297	0.4995	0.8843
0.4883	0.7373	0.8843
−0.0391	0.8835	0.8843
−0.2668	0.8431	0.8843
−0.4763	0.7451	0.8843
−0.6533	0.5961	0.8843
−0.7855	0.4063	0.8843
−0.8640	0.1887	0.8843
−0.8834	−0.0418	0.8843
−0.8423	−0.2695	0.8843
−0.7430	−0.4796	0.8843
−0.5932	−0.6559	0.8843
−0.4029	−0.7873	0.8843
−0.1849	−0.8648	0.8843
0.0457	−0.8832	0.8843
0.2731	−0.8411	0.8843
0.4819	−0.7415	0.8843
0.6577	−0.5912	0.8843
0.7909	−0.3957	0.8843
0.8664	−0.1771	0.8843

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TABLE 1e-continued

60 lenslets
density of lenslets 0.8388
radius of lenslets 0.0649

x	y	distance to center

TABLE 1f

61 lenslets
density of lenslets 0.8414
radius of lenslets 0.0598

x	y	distance to center
0.0000	0.0000	0.0000
0.2230	0.0598	0.2309
0.0598	0.2230	0.2309
-0.1633	0.1633	0.2309
-0.2230	-0.0598	0.2309
-0.0598	-0.2230	0.2309
0.1633	-0.1633	0.2309
0.4461	0.0000	0.4461
0.0000	0.4461	0.4461
0.3863	0.2230	0.4461
0.2230	0.3863	0.4461
-0.2230	0.3863	0.4461
-0.3863	0.2230	0.4461
-0.4461	0.0000	0.4461
0.0000	-0.4461	0.4461
-0.3863	-0.2230	0.4461
-0.2230	-0.3863	0.4461
0.2230	-0.3863	0.4461
0.3863	-0.2230	0.4461
0.6172	0.2230	0.6563
0.5018	0.4230	0.6563
0.1155	0.6461	0.6563
-0.1155	0.6461	0.6563
-0.5018	0.4230	0.6563
-0.6172	0.2230	0.6563
-0.6172	-0.2230	0.6563
-0.5018	-0.4230	0.6563
-0.1155	-0.6461	0.6563
0.1155	-0.6461	0.6563
0.5018	-0.4230	0.6563
0.6172	-0.2230	0.6563
0.6770	0.0000	0.6770
0.3385	0.5863	0.6770
-0.3385	0.5863	0.6770
-0.6770	0.0000	0.6770
-0.3385	-0.5863	0.6770
0.3385	-0.5863	0.6770
0.8770	0.1155	0.8845
0.8172	0.3385	0.8845
0.7018	0.5385	0.8845
0.5385	0.7018	0.8845
0.3385	0.8172	0.8845
0.1155	0.8770	0.8845
-0.1155	0.8770	0.8845
-0.3385	0.8172	0.8845
-0.5385	0.7018	0.8845
-0.7018	0.5385	0.8845
-0.8172	0.3385	0.8845
-0.8770	0.1155	0.8845
-0.8770	-0.1155	0.8845
-0.8172	-0.3385	0.8845
-0.7018	-0.5385	0.8845
-0.5385	-0.7018	0.8845
-0.3385	-0.8172	0.8845
-0.1155	-0.8770	0.8845
0.1155	-0.8770	0.8845
0.3385	-0.8172	0.8845
0.5385	-0.7018	0.8845
0.7018	-0.5385	0.8845
0.8172	-0.3385	0.8845
0.8770	-0.1155	0.8845

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TABLE 1g

90 lenslets
density of lenslets 0.8388
radius of lenslets 0.0649

x	y	distance to center
-0.0006	0.0024	0.0025
0.0865	-0.1662	0.1873
-0.1033	-0.1570	0.1880
0.1889	-0.0057	0.1889
-0.1900	0.0116	0.1904
0.0998	0.1633	0.1914
-0.0897	0.1725	0.1944
0.0206	-0.3441	0.3447
0.3093	-0.1522	0.3447
-0.2906	-0.1864	0.3453
0.2869	0.1939	0.3463
-0.3075	0.1608	0.3470
0.2076	-0.3122	0.3749
-0.1688	-0.3350	0.3751
0.3758	0.0264	0.3767
-0.3774	-0.0178	0.3778
0.1617	0.3426	0.3788
-0.2057	0.3225	0.3825
-0.0246	0.3819	0.3827
0.3912	-0.3596	0.5314
-0.5084	-0.1549	0.5315
-0.4216	-0.3235	0.5315
-0.1181	-0.5182	0.5315
0.0713	-0.5268	0.5316
0.5056	0.1646	0.5317
0.4930	-0.1996	0.5318
0.4168	0.3321	0.5329
-0.4925	0.2101	0.5355
-0.3895	0.3693	0.5367
0.1115	0.5254	0.5371
0.2583	-0.4949	0.5583
-0.3016	-0.4704	0.5588
0.5592	-0.0219	0.5596
-0.5601	0.0329	0.5611
0.2950	0.4775	0.5613
-0.2532	0.5061	0.5659
-0.0736	0.5669	0.5716
0.5946	0.3981	0.7155
-0.5983	-0.3924	0.7155
0.0426	-0.7143	0.7155
0.6408	-0.3184	0.7155
-0.6309	0.3398	0.7166
-0.6985	0.1626	0.7172
0.4728	0.5435	0.7203
0.5390	-0.4784	0.7207
-0.6851	-0.2238	0.7208
-0.4783	-0.5392	0.7208
-0.1468	-0.7057	0.7208
0.2297	-0.6832	0.7208
0.7070	-0.1406	0.7209
0.6834	0.2306	0.7212
0.1364	0.7134	0.7264
-0.2143	0.6940	0.7264
-0.5279	0.4990	0.7264
0.4061	-0.6137	0.7359
-0.7349	-0.0408	0.7360
-0.3303	-0.6578	0.7361
0.7354	0.0482	0.7370
0.3199	0.6655	0.7384
-0.3939	0.6332	0.7457
-0.0429	0.7752	0.7764
0.2902	0.8573	0.9051
0.8917	0.1556	0.9052
0.8397	0.3379	0.9052
0.7509	0.5055	0.9052
0.6291	0.6508	0.9052
0.4797	0.7676	0.9052
0.1003	0.8996	0.9052
-0.1989	0.8831	0.9052
-0.3785	0.8222	0.9052
-0.5703	0.7030	0.9052
-0.7042	0.5687	0.9052
-0.8073	0.4095	0.9052
-0.8749	0.2323	0.9052

TABLE 1g-continued

90 lenslets
density of lenslets 0.8388
radius of lenslets 0.0649

x	y	distance to center
−0.9041	0.0449	0.9052
−0.8935	−0.1447	0.9052
−0.8438	−0.3277	0.9052
−0.7570	−0.4963	0.9052
−0.6370	−0.6431	0.9052
−0.4890	−0.7617	0.9052
−0.3189	−0.8471	0.9052
−0.1354	−0.8950	0.9052
0.0540	−0.9036	0.9052
0.2411	−0.8725	0.9052
0.4176	−0.8031	0.9052
0.5758	−0.6985	0.9052
0.7087	−0.5632	0.9052
0.8104	−0.4031	0.9052
0.8767	−0.2254	0.9052
0.9044	−0.0378	0.9052

TABLE 1h

91 lenslets
density of lenslets 0.8414
radius of lenslets 0.0598

x	y	distance to center
0.0000	0.0000	0.0000
0.1893	0.0000	0.1893
0.0946	0.1639	0.1893
−0.0946	0.1639	0.1893
−0.1893	0.0000	0.1893
−0.0946	−0.1639	0.1893
0.0946	−0.1639	0.1893
0.3159	0.1407	0.3458
0.0361	0.3439	0.3458
−0.2798	0.2033	0.3458
−0.3159	−0.1407	0.3458
−0.0361	−0.3439	0.3458
0.2798	−0.2033	0.3458
0.2213	0.3046	0.3765
−0.1531	0.3439	0.3765
−0.3744	0.0394	0.3765
−0.2213	−0.3046	0.3765
0.1531	−0.3439	0.3765
0.3744	−0.0394	0.3765
0.4888	0.2176	0.5351
0.0559	0.5322	0.5351
−0.4329	0.3145	0.5351
−0.4888	−0.2176	0.5351
−0.0559	−0.5322	0.5351
0.4329	−0.3145	0.5351
0.5473	0.0376	0.5486
0.3942	0.3816	0.5486
0.2411	0.4928	0.5486
−0.1333	0.5322	0.5486
−0.3062	0.4552	0.5486
−0.5275	0.1506	0.5486
−0.5473	−0.0376	0.5486
−0.3942	−0.3816	0.5486
−0.2411	−0.4928	0.5486
0.1333	−0.5322	0.5486
0.3062	−0.4552	0.5486
0.5275	−0.1506	0.5486
0.5793	0.4209	0.7161
−0.0749	0.7122	0.7161
−0.6542	0.2913	0.7161
−0.5793	−0.4209	0.7161
0.0749	−0.7122	0.7161
0.6542	−0.2913	0.7161
0.6740	0.2570	0.7213
0.4527	0.5616	0.7213
0.1144	0.7122	0.7213

TABLE 1h-continued

91 lenslets
density of lenslets 0.8414
radius of lenslets 0.0598

x	y	distance to center
−0.2600	0.6728	0.7213
−0.5595	0.4552	0.7213
−0.7127	0.1113	0.7213
−0.6740	−0.2570	0.7213
−0.4527	−0.5616	0.7213
−0.1144	−0.7122	0.7213
0.2600	−0.6728	0.7213
0.5595	−0.4552	0.7213
0.7127	−0.1113	0.7213
0.7325	0.0770	0.7365
0.2996	0.6728	0.7365
−0.4329	0.5958	0.7365
−0.7325	−0.0770	0.7365
−0.2996	−0.6728	0.7365
0.4329	−0.5958	0.7365
0.9054	0.0000	0.9054
0.8856	0.1882	0.9054
0.8271	0.3682	0.9054
0.7325	0.5322	0.9054
0.6058	0.6728	0.9054
0.4527	0.7841	0.9054
0.2798	0.8611	0.9054
0.0946	0.9004	0.9054
−0.0946	0.9004	0.9054
−0.2798	0.8611	0.9054
−0.4527	0.7841	0.9054
−0.6058	0.6728	0.9054
−0.7325	0.5322	0.9054
−0.8271	0.3682	0.9054
−0.8856	0.1882	0.9054
−0.9054	0.0000	0.9054
−0.8856	−0.1882	0.9054
−0.8271	−0.3682	0.9054
−0.7325	−0.5322	0.9054
−0.6058	−0.6728	0.9054
−0.4527	−0.7841	0.9054
−0.2798	−0.8611	0.9054
−0.0946	−0.9004	0.9054
0.0946	−0.9004	0.9054
0.2798	−0.8611	0.9054
0.4527	−0.7841	0.9054
0.6058	−0.6728	0.9054
0.7325	−0.5322	0.9054
0.8271	−0.3682	0.9054
0.8856	−0.1882	0.9054

TABLE 1i

121 lenslets
density of lenslets 0.8388
radius of lenslets 0.0649

x	y	distance to center
0.0000	0.0000	0.0000
0.1543	0.0582	0.1650
0.0268	0.1628	0.1650
−0.1276	0.1046	0.1650
−0.1543	−0.0582	0.1650
−0.0268	−0.1628	0.1650
0.1276	−0.1046	0.1650
0.1811	0.2210	0.2857
−0.1008	0.2673	0.2857
−0.2819	0.0463	0.2857
−0.1811	−0.2210	0.2857
0.1008	−0.2673	0.2857
0.2819	−0.0463	0.2857
0.3087	0.1164	0.3299
0.0535	0.3255	0.3299
−0.2552	0.2091	0.3299
−0.3087	−0.1164	0.3299

TABLE 1i-continued

	121 lenslets density of lenslets 0.8388 radius of lenslets 0.0649	
x	y	distance to center
−0.0535	−0.3255	0.3299
0.2552	−0.2091	0.3299
0.4363	0.0119	0.4364
0.3354	0.2792	0.4364
0.2078	0.3837	0.4364
−0.0741	0.4301	0.4364
−0.2284	0.3719	0.4364
−0.4095	0.1509	0.4364
−0.4363	−0.0119	0.4364
−0.3354	−0.2792	0.4364
−0.2078	−0.3837	0.4364
0.0741	−0.4301	0.4364
0.2284	−0.3719	0.4364
0.4095	−0.1509	0.4364
0.4630	0.1746	0.4949
0.0803	0.4883	0.4949
−0.3827	0.3137	0.4949
−0.4630	−0.1746	0.4949
−0.0803	−0.4883	0.4949
0.3827	−0.3137	0.4949
0.5912	0.0684	0.5952
0.2364	0.5462	0.5952
−0.3548	0.4778	0.5952
−0.5912	−0.0684	0.5952
−0.2364	−0.5462	0.5952
0.3548	−0.4778	0.5952
0.4855	0.3476	0.5971
−0.0582	0.5943	0.5971
−0.5438	0.2467	0.5971
−0.4855	−0.3476	0.5971
0.0582	−0.5943	0.5971
0.5438	−0.2467	0.5971
0.3876	0.4803	0.6172
−0.2222	0.5758	0.6172
0.3087	0.1164	0.3299
0.0535	0.3255	0.3299
−0.2552	0.2091	0.3299
−0.3087	−0.1164	0.3299
−0.0535	−0.3255	0.3299
0.2552	−0.2091	0.3299
0.4363	0.0119	0.4364
0.3354	0.2792	0.4364
0.2078	0.3837	0.4364
−0.0741	0.4301	0.4364
−0.2284	0.3719	0.4364
−0.4095	0.1509	0.4364
−0.4363	−0.0119	0.4364
−0.3354	−0.2792	0.4364
−0.2078	−0.3837	0.4364
0.0741	−0.4301	0.4364
0.2284	−0.3719	0.4364
0.4095	−0.1509	0.4364
0.4630	0.1746	0.4949
0.0803	0.4883	0.4949
−0.3827	0.3137	0.4949
−0.4630	−0.1746	0.4949
−0.0803	−0.4883	0.4949
0.3827	−0.3137	0.4949
0.5912	0.0684	0.5952
0.2364	0.5462	0.5952
−0.3548	0.4778	0.5952
−0.5912	−0.0684	0.5952
−0.2364	−0.5462	0.5952
0.3548	−0.4778	0.5952
0.4855	0.3476	0.5971
−0.0582	0.5943	0.5971
−0.5438	0.2467	0.5971
−0.4855	−0.3476	0.5971
0.0582	−0.5943	0.5971
0.5438	−0.2467	0.5971
0.3876	0.4803	0.6172
−0.2222	0.5758	0.6172
−0.6098	0.0955	0.6172
−0.3876	−0.4803	0.6172

TABLE 1i-continued

	121 lenslets density of lenslets 0.8388 radius of lenslets 0.0649	
x	y	distance to center
0.2222	−0.5758	0.6172
0.6098	−0.0955	0.6172
0.6180	0.2312	0.6598
0.1088	0.6508	0.6598
−0.5092	0.4196	0.6598
−0.6180	−0.2312	0.6598
−0.1088	−0.6508	0.6598
0.5092	−0.4196	0.6598
0.6438	0.3941	0.7548
−0.0194	0.7546	0.7548
−0.6632	0.3605	0.7548
−0.6438	−0.3941	0.7548
0.0194	−0.7546	0.7548
0.6632	−0.3605	0.7548
0.7498	0.1138	0.7584
0.2763	0.7063	0.7584
−0.4735	0.5924	0.7584
−0.7498	−0.1138	0.7584
−0.2763	−0.7063	0.7584
0.4735	−0.5924	0.7584
0.5498	0.5296	0.7634
−0.1838	0.7409	0.7634
−0.7335	0.2113	0.7634
−0.5498	−0.5296	0.7634
0.1838	−0.7409	0.7634
0.7335	−0.2113	0.7634
0.4275	0.6404	0.7700
−0.3408	0.6904	0.7700
−0.7683	0.0501	0.7700
−0.4275	−0.6404	0.7700
0.3408	−0.6904	0.7700
0.7683	−0.0501	0.7700
0.7720	0.2903	0.8247
0.1346	0.8137	0.8247
−0.6374	0.5234	0.8247
−0.7720	−0.2903	0.8247
−0.1346	−0.8137	0.8247
0.6374	−0.5234	0.8247
0.5814	0.7089	0.9169
−0.3233	0.8580	0.9169
−0.9047	0.1491	0.9169
−0.5814	−0.7089	0.9169
0.3233	−0.8580	0.9169
0.9047	−0.1491	0.9169
0.9173	0.0208	0.9175
0.8987	0.1847	0.9175
0.7978	0.4532	0.9175
0.7038	0.5887	0.9175
0.4406	0.8048	0.9175
0.2894	0.8707	0.9175
0.0064	0.9175	0.9175
−0.1579	0.9038	0.9175
−0.4767	0.7840	0.9175
−0.6093	0.6860	0.9175
−0.7914	0.4643	0.9175
−0.8617	0.3151	0.9175
−0.9173	−0.0208	0.9175
−0.8987	−0.1847	0.9175
−0.7978	−0.4532	0.9175
−0.7038	−0.5887	0.9175
−0.4406	−0.8048	0.9175
−0.2894	−0.8707	0.9175
−0.0064	−0.9175	0.9175
0.1579	−0.9038	0.9175
0.4767	−0.7840	0.9175
0.6093	−0.6860	0.9175
0.7914	−0.4643	0.9175
0.8617	−0.3151	0.9175

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TABLE 1j

151 lenslets density of lenslets 0.8414 radius of lenslets 0.0598		
x	y	distance to center
0.0000	0.0000	0.0000
0.1171	0.0912	0.1484
-0.0204	0.1470	0.1484
-0.1375	0.0558	0.1484
-0.1171	-0.0912	0.1484
0.0204	-0.1470	0.1484
0.1375	-0.0558	0.1484
0.2546	0.0354	0.2571
0.0967	0.2382	0.2571
-0.1579	0.2028	0.2571
-0.2546	-0.0354	0.2571
-0.0967	-0.2382	0.2571
0.1579	-0.2028	0.2571
0.2342	0.1824	0.2968
-0.0408	0.2940	0.2968
-0.2750	0.1116	0.2968
-0.2342	-0.1824	0.2968
0.0408	-0.2940	0.2968
0.2750	-0.1116	0.2968
0.3717	0.1265	0.3927
0.2138	0.3294	0.3927
0.0763	0.3852	0.3927
-0.1783	0.3498	0.3927
-0.2954	0.2586	0.3927
-0.3921	0.0205	0.3927
-0.3717	-0.1265	0.3927
-0.2138	-0.3294	0.3927
-0.0763	-0.3852	0.3927
0.1783	-0.3498	0.3927
0.2954	-0.2586	0.3927
0.3921	-0.0205	0.3927
0.3513	0.2735	0.4452
-0.0612	0.4410	0.4452
-0.4125	0.1675	0.4452
-0.3513	-0.2735	0.4452
0.0612	-0.4410	0.4452
0.4125	-0.1675	0.4452
0.5092	0.0707	0.5141
0.1934	0.4764	0.5141
-0.3159	0.4056	0.5141
-0.5092	-0.0707	0.5141
-0.1934	-0.4764	0.5141
0.3159	-0.4056	0.5141
0.4888	0.2177	0.5351
0.3309	0.4205	0.5351
0.0559	0.5322	0.5351
-0.1988	0.4968	0.5351
-0.4330	0.3145	0.5351
-0.5296	0.0763	0.5351
-0.4888	-0.2177	0.5351
-0.3309	-0.4205	0.5351
0.2342	0.1824	0.2968
-0.0408	0.2940	0.2968
-0.2750	0.1116	0.2968
-0.2342	-0.1824	0.2968
0.0408	-0.2940	0.2968
0.2750	-0.1116	0.2968
0.3717	0.1265	0.3927
0.2138	0.3294	0.3927
0.0763	0.3852	0.3927
-0.1783	0.3498	0.3927
-0.2954	0.2586	0.3927
-0.3921	0.0205	0.3927
-0.3717	-0.1265	0.3927
-0.2138	-0.3294	0.3927
-0.0763	-0.3852	0.3927
0.1783	-0.3498	0.3927
0.2954	-0.2586	0.3927
0.3921	-0.0205	0.3927
0.3513	0.2735	0.4452
-0.0612	0.4410	0.4452
-0.4125	0.1675	0.4452
-0.3513	-0.2735	0.4452
0.0612	-0.4410	0.4452

TABLE 1j-continued

151 lenslets density of lenslets 0.8414 radius of lenslets 0.0598		
x	y	distance to center
0.4125	-0.1675	0.4452
0.5092	0.0707	0.5141
0.1934	0.4764	0.5141
-0.3159	0.4056	0.5141
-0.5092	-0.0707	0.5141
-0.1934	-0.4764	0.5141
0.3159	-0.4056	0.5141
0.4888	0.2177	0.5351
0.3309	0.4205	0.5351
0.0559	0.5322	0.5351
-0.1988	0.4968	0.5351
-0.4330	0.3145	0.5351
-0.5296	0.0763	0.5351
-0.4888	-0.2177	0.5351
-0.3309	-0.4205	0.5351
-0.0559	-0.5322	0.5351
0.1988	-0.4968	0.5351
0.4330	-0.3145	0.5351
0.5296	-0.0763	0.5351
0.4684	0.3647	0.5936
-0.0817	0.5880	0.5936
-0.5501	0.2233	0.5936
-0.4684	-0.3647	0.5936
0.0817	-0.5880	0.5936
0.5501	-0.2233	0.5936
0.6467	0.0149	0.6469
0.6263	0.1619	0.6469
0.3105	0.5675	0.6469
0.1729	0.6234	0.6469
-0.3363	0.5526	0.6469
-0.4534	0.4615	0.6469
-0.6467	-0.0149	0.6469
-0.6263	-0.1619	0.6469
-0.3105	-0.5675	0.6469
-0.1729	-0.6234	0.6469
0.3363	-0.5526	0.6469
0.4534	-0.4615	0.6469
0.6059	0.3089	0.6801
0.0354	0.6792	0.6801
-0.5705	0.3703	0.6801
-0.6059	-0.3089	0.6801
-0.0354	-0.6792	0.6801
0.5705	-0.3703	0.6801
0.6701	-0.1317	0.6829
0.4495	0.5154	0.6839
-0.2216	0.6470	0.6839
-0.6711	0.1315	0.6839
-0.4495	-0.5154	0.6839
0.2217	-0.6470	0.6839
0.5855	0.4559	0.7420
-0.1021	0.7350	0.7420
-0.6876	0.2791	0.7420
-0.5855	-0.4559	0.7420
0.1021	-0.7350	0.7420
0.6876	-0.2791	0.7420
0.7434	0.2531	0.7853
0.1525	0.7704	0.7853
-0.5909	0.5173	0.7853
-0.7434	-0.2531	0.7853
-0.1525	-0.7704	0.7853
0.5909	-0.5173	0.7853
0.4249	0.6621	0.7867
-0.3609	0.6990	0.7867
-0.7858	0.0369	0.7867
-0.4249	-0.6621	0.7867
0.3609	-0.6990	0.7867
0.7858	-0.0369	0.7867
0.7878	0.1115	0.7957
0.2974	0.7380	0.7957
-0.4905	0.6266	0.7957
-0.7878	-0.1115	0.7957
-0.2974	-0.7380	0.7957
0.4905	-0.6266	0.7957
0.5854	0.6043	0.8413

TABLE 1j-continued

	151 lenslets density of lenslets 0.8414 radius of lenslets 0.0598	
x	y	distance to center
−0.2307	0.8091	0.8413
−0.8160	0.2048	0.8413
−0.5854	−0.6043	0.8413
0.2307	−0.8091	0.8413
0.8160	−0.2048	0.8413
0.0000	0.8427	0.8427
0.7298	0.4214	0.8427
−0.7298	0.4214	0.8427
0.0000	−0.8427	0.8427
−0.7298	−0.4214	0.8427
0.7298	−0.4214	0.8427
−0.4182	−0.8249	0.9248
−0.9240	−0.0512	0.9254
−0.5055	0.7753	0.9255
0.5063	−0.7748	0.9255
0.4192	0.8254	0.9257
0.9245	0.0493	0.9258
0.9027	0.2054	0.9258
0.8583	0.3470	0.9258
0.7297	0.5698	0.9258
0.5462	0.7475	0.9258
0.2734	0.8845	0.9258
0.1286	0.9168	0.9258
−0.1286	0.9168	0.9258
−0.3742	0.8468	0.9258
−0.6293	0.6790	0.9258
−0.7297	0.5698	0.9258
−0.8583	0.3470	0.9258
−0.9205	0.0993	0.9258
−0.9027	−0.2054	0.9258
−0.8583	−0.3470	0.9258
−0.7297	−0.5698	0.9258
−0.5462	−0.7475	0.9258
−0.2734	−0.8845	0.9258
−0.1286	−0.9168	0.9258
0.1286	−0.9168	0.9258
0.3742	−0.8468	0.9258
0.6293	−0.6790	0.9258
0.7297	−0.5698	0.9258
0.8583	−0.3470	0.9258
0.9205	−0.0993	0.9258

TABLE 1l

	235 lenslets density of lenslets 0.8414 radius of lenslets 0.0598	
x	y	distance to center
0.0000	0.0000	0.0000
0.1197	0.0000	0.1197
0.0598	0.1036	0.1197
−0.0598	0.1036	0.1197
−0.1197	0.0000	0.1197
−0.0598	−0.1036	0.1197
0.0598	−0.1036	0.1197
0.0000	0.2073	0.2073
0.1795	0.1036	0.2073
−0.1795	0.1036	0.2073
0.0000	−0.2073	0.2073
−0.1795	−0.1036	0.2073
0.1795	−0.1036	0.2073
0.2393	0.0000	0.2393
0.1197	0.2073	0.2393
−0.1197	0.2073	0.2393
−0.2393	0.0000	0.2393
−0.1197	−0.2073	0.2393
0.1197	−0.2073	0.2393
0.2992	0.1036	0.3166
0.2393	0.2073	0.3166

TABLE 1l-continued

	235 lenslets density of lenslets 0.8414 radius of lenslets 0.0598	
x	y	distance to center
0.0598	0.3109	0.3166
−0.0598	0.3109	0.3166
−0.2393	0.2073	0.3166
−0.2992	0.1036	0.3166
−0.2992	−0.1036	0.3166
−0.2393	−0.2073	0.3166
−0.0598	−0.3109	0.3166
0.0598	−0.3109	0.3166
0.2393	−0.2073	0.3166
0.2992	−0.1036	0.3166
0.3590	0.0000	0.3590
0.1795	0.3109	0.3590
−0.1795	0.3109	0.3590
−0.3590	0.0000	0.3590
−0.1795	−0.3109	0.3590
0.1795	−0.3109	0.3590
0.0000	0.4146	0.4146
0.3590	0.2073	0.4146
−0.3590	0.2073	0.4146
0.0000	−0.4146	0.4146
−0.3590	−0.2073	0.4146
0.3590	−0.2073	0.4146
0.4188	0.1036	0.4315
0.2992	0.3109	0.4315
0.1197	0.4146	0.4315
−0.1197	0.4146	0.4315
−0.2992	0.3109	0.4315
−0.4188	0.1036	0.4315
−0.4188	−0.1036	0.4315
−0.2992	−0.3109	0.4315
−0.1197	−0.4146	0.4315
0.1197	−0.4146	0.4315
0.2992	−0.3109	0.4315
0.4188	−0.1036	0.4315
0.4787	0.0000	0.4787
0.2393	0.4146	0.4787
−0.2393	0.4146	0.4787
−0.4787	0.0000	0.4787
−0.2393	−0.4146	0.4787
0.2393	−0.4146	0.4787
0.4787	0.2073	0.5216
0.4188	0.3109	0.5216
0.0598	0.5182	0.5216
−0.0598	0.5182	0.5216
−0.4188	0.3109	0.5216
−0.4787	0.2073	0.5216
−0.4787	−0.2073	0.5216
−0.4188	−0.3109	0.5216
−0.0598	−0.5182	0.5216
0.0598	−0.5182	0.5216
0.4188	−0.3109	0.5216
0.4787	−0.2073	0.5216
0.5385	0.1036	0.5484
0.3590	0.4146	0.5484
0.1795	0.5182	0.5484
−0.1795	0.5182	0.5484
−0.3590	0.4146	0.5484
−0.5385	0.1036	0.5484
−0.5385	−0.1036	0.5484
−0.3590	−0.4146	0.5484
−0.1795	−0.5182	0.5484
0.1795	−0.5182	0.5484
0.3590	−0.4146	0.5484
0.5385	−0.1036	0.5484
0.5984	0.0000	0.5984
0.2992	0.5182	0.5984
−0.2992	0.5182	0.5984
−0.5984	0.0000	0.5984
−0.2992	−0.5182	0.5984
0.2992	−0.5182	0.5984
0.0000	0.6218	0.6218
0.5385	0.3109	0.6218
−0.5385	0.3109	0.6218
0.0000	−0.6218	0.6218

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TABLE 11-continued

235 lenslets
density of lenslets 0.8414
radius of lenslets 0.0598

x	y	distance to center
−0.5385	−0.3109	0.6218
0.5385	−0.3109	0.6218
0.5984	0.2073	0.6332
0.4787	0.4146	0.6332
0.1197	0.6218	0.6332
−0.1197	0.6218	0.6332
−0.4787	0.4146	0.6332
−0.5984	0.2073	0.6332
−0.5984	−0.2073	0.6332
−0.4787	−0.4146	0.6332
−0.1197	−0.6218	0.6332
0.1197	−0.6218	0.6332
0.4787	−0.4146	0.6332
0.5984	−0.2073	0.6332
0.6582	0.1036	0.6663
0.4188	0.5182	0.6663
0.2393	0.6218	0.6663
−0.2393	0.6218	0.6663
−0.4188	0.5182	0.6663
−0.6582	0.1036	0.6663
−0.6582	−0.1036	0.6663
−0.4188	−0.5182	0.6663
−0.2393	−0.6218	0.6663
0.2393	−0.6218	0.6663
0.4188	−0.5182	0.6663
0.6582	−0.1036	0.6663
0.7180	0.0000	0.7180
0.3590	0.6218	0.7180
−0.3590	0.6218	0.7180
−0.7180	0.0000	0.7180
−0.3590	−0.6218	0.7180
0.3590	−0.6218	0.7180
0.6582	0.3109	0.7279
0.5984	0.4146	0.7279
0.0598	0.7255	0.7279
−0.0598	0.7255	0.7279
−0.5984	0.4146	0.7279
−0.6582	0.3109	0.7279
−0.6582	−0.3109	0.7279
−0.5984	−0.4146	0.7279
−0.0598	−0.7255	0.7279
0.0598	−0.7255	0.7279
0.5984	−0.4146	0.7279
0.6582	−0.3109	0.7279
0.7185	0.2075	0.7478
0.5389	0.5184	0.7478
0.1795	0.7260	0.7478
−0.1795	0.7260	0.7478
−0.5389	0.5184	0.7478
−0.7185	0.2075	0.7478
−0.7185	−0.2075	0.7478
−0.5389	−0.5184	0.7478
−0.1795	−0.7260	0.7478
0.1795	−0.7260	0.7478
0.5389	−0.5184	0.7478
0.7185	−0.2075	0.7478
0.7779	0.1036	0.7847
0.4787	0.6218	0.7847
0.2992	0.7255	0.7847
−0.2992	0.7255	0.7847
−0.4787	0.6218	0.7847
−0.7779	0.1036	0.7847
−0.7779	−0.1036	0.7847
−0.4787	−0.6218	0.7847
−0.2992	−0.7255	0.7847
0.2992	−0.7255	0.7847
0.4787	−0.6218	0.7847
0.7779	−0.1036	0.7847
0.8377	0.0000	0.8377
0.4188	0.7255	0.8377
−0.4188	0.7255	0.8377
−0.8377	0.0000	0.8377
−0.4188	−0.7255	0.8377
0.4188	−0.7255	0.8377

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TABLE 11-continued

235 lenslets
density of lenslets 0.8414
radius of lenslets 0.0598

x	y	distance to center
0.7779	0.3114	0.8379
0.6586	0.5179	0.8379
0.1192	0.8293	0.8379
−0.1192	0.8293	0.8379
−0.6586	0.5179	0.8379
−0.7779	0.3114	0.8379
−0.7779	−0.3114	0.8379
−0.6586	−0.5179	0.8379
−0.1192	−0.8293	0.8379
0.1192	−0.8293	0.8379
0.6586	−0.5179	0.8379
0.7779	−0.3114	0.8379
0.0000	0.8395	0.8395
0.7270	0.4197	0.8395
−0.7270	0.4197	0.8395
0.0000	−0.8395	0.8395
−0.7270	−0.4197	0.8395
0.7270	−0.4197	0.8395
0.8780	0.1691	0.8942
0.5855	0.6759	0.8942
0.2926	0.8450	0.8942
−0.2926	0.8450	0.8942
−0.5855	0.6759	0.8942
−0.8780	0.1691	0.8942
−0.8780	−0.1691	0.8942
−0.5855	−0.6759	0.8942
−0.2926	−0.8450	0.8942
0.2926	−0.8450	0.8942
0.5855	−0.6759	0.8942
0.8780	−0.1691	0.8942
0.9379	0.0654	0.9402
0.8951	0.2875	0.9402
0.8462	0.4096	0.9402
0.7779	0.5281	0.9402
0.6966	0.6314	0.9402
0.5256	0.7795	0.9402
0.4123	0.8450	0.9402
0.1986	0.9190	0.9402
0.0684	0.9377	0.9402
−0.0684	0.9377	0.9402
−0.1986	0.9190	0.9402
−0.4123	0.8450	0.9402
−0.5256	0.7795	0.9402
−0.6966	0.6314	0.9402
−0.7779	0.5281	0.9402
−0.8462	0.4096	0.9402
−0.8951	0.2875	0.9402
−0.9379	0.0654	0.9402
−0.9379	−0.0654	0.9402
−0.8951	−0.2875	0.9402
−0.8462	−0.4096	0.9402
−0.7779	−0.5281	0.9402
−0.6966	−0.6314	0.9402
−0.5256	−0.7795	0.9402
−0.4123	−0.8450	0.9402
−0.1986	−0.9190	0.9402
−0.0684	−0.9377	0.9402
0.0684	−0.9377	0.9402
0.1986	−0.9190	0.9402
0.4123	−0.8450	0.9402
0.5256	−0.7795	0.9402
0.6966	−0.6314	0.9402
0.7779	−0.5281	0.9402
0.8462	−0.4096	0.9402
0.8951	−0.2875	0.9402
0.9379	−0.0654	0.9402

TABLE 1k

199 lenslets density of lenslets 0.8388 radius of lenslets 0.0649		
x	y	distance to center
0.0000	0.0000	0.0000
0.0930	0.0906	0.1299
−0.0320	0.1259	0.1299
−0.1250	0.0352	0.1299
−0.0930	−0.0906	0.1299
0.0320	−0.1259	0.1299
0.1250	−0.0352	0.1299
0.2180	0.0554	0.2249
0.0610	0.2165	0.2249
−0.1570	0.1611	0.2249
−0.2180	−0.0554	0.2249
−0.0610	−0.2165	0.2249
0.1570	−0.1611	0.2249
0.1860	0.1812	0.2597
−0.0640	0.2517	0.2597
−0.2500	0.0705	0.2597
−0.1860	−0.1812	0.2597
0.0640	−0.2517	0.2597
0.2500	−0.0705	0.2597
0.3430	0.0202	0.3436
0.3110	0.1460	0.3436
0.1540	0.3071	0.3436
0.0290	0.3423	0.3436
−0.1889	0.2869	0.3436
−0.2819	0.1963	0.3436
−0.3430	−0.0202	0.3436
−0.3110	−0.1460	0.3436
−0.1540	−0.3071	0.3436
−0.0290	−0.3423	0.3436
0.1889	−0.2869	0.3436
0.2819	−0.1963	0.3436
0.2790	0.2719	0.3896
−0.0959	0.3776	0.3896
−0.3749	0.1057	0.3896
−0.2790	−0.2719	0.3896
0.0959	−0.3776	0.3896
0.3749	−0.1057	0.3896
0.4360	0.1108	0.4498
0.1220	0.4329	0.4498
−0.3139	0.3222	0.4498
−0.4360	−0.1108	0.4498
−0.1220	−0.4329	0.4498
0.3139	−0.3222	0.4498
0.4040	0.2366	0.4682
0.2470	0.3977	0.4682
−0.0030	0.4682	0.4682
−0.2209	0.4128	0.4682
−0.4069	0.2315	0.4682
−0.4679	0.0151	0.4682
−0.4040	−0.2366	0.4682
−0.2470	−0.3977	0.4682
0.0030	−0.4682	0.4682
0.2209	−0.4128	0.4682
0.4069	−0.2315	0.4682
0.4679	−0.0151	0.4682
0.3720	0.3625	0.5194
−0.1279	0.5034	0.5194
−0.4999	0.1409	0.5194
−0.3720	−0.3625	0.5194
0.1279	−0.5034	0.5194
0.4999	−0.1409	0.5194
0.5609	0.0756	0.5660
0.5290	0.2014	0.5660
0.2150	0.5236	0.5660
0.0900	0.5588	0.5660
−0.3459	0.4480	0.5660
−0.4389	0.3574	0.5660
−0.5609	−0.0756	0.5660
−0.5290	−0.2014	0.5660
−0.2150	−0.5236	0.5660
−0.0900	−0.5588	0.5660
0.3459	−0.4480	0.5660
0.4389	−0.3574	0.5660
0.4970	0.3273	0.5951

TABLE 1k-continued

199 lenslets density of lenslets 0.8388 radius of lenslets 0.0649		
x	y	distance to center
−0.0349	0.5940	0.5951
−0.5319	0.2668	0.5951
−0.4970	−0.3273	0.5951
0.0349	−0.5940	0.5951
0.5319	−0.2668	0.5951
0.3405	0.4902	0.5968
−0.2542	0.5400	0.5968
−0.5948	0.0498	0.5968
−0.3405	−0.4902	0.5968
0.2542	−0.5400	0.5968
0.5948	−0.0498	0.5968
0.4650	0.4531	0.6493
−0.1599	0.6292	0.6493
−0.6249	0.1761	0.6493
−0.4650	−0.4531	0.6493
0.1599	−0.6292	0.6493
0.6249	−0.1761	0.6493
0.6220	0.2920	0.6871
0.0581	0.6846	0.6871
−0.5639	0.3926	0.6871
−0.6220	−0.2920	0.6871
−0.0581	−0.6846	0.6871
0.5639	−0.3926	0.6871
0.6875	0.0464	0.6890
0.3036	0.6185	0.6890
−0.3839	0.5722	0.6890
−0.6875	−0.0464	0.6890
−0.3036	−0.6185	0.6890
0.3839	−0.5722	0.6890
0.6803	0.1760	0.7027
0.1877	0.6771	0.7027
−0.4926	0.5011	0.7027
−0.6803	−0.1760	0.7027
−0.1877	−0.6771	0.7027
0.4926	−0.5011	0.7027
0.5900	0.4179	0.7230
−0.0669	0.7199	0.7230
−0.6569	0.3020	0.7230
−0.5900	−0.4179	0.7230
0.0669	−0.7199	0.7230
0.6569	−0.3020	0.7230
0.4299	0.5843	0.7255
−0.2911	0.6645	0.7255
−0.7210	0.0802	0.7255
−0.4299	−0.5843	0.7255
0.2911	−0.6645	0.7255
0.7210	−0.0802	0.7255
0.5544	0.5473	0.7790
−0.1968	0.7538	0.7790
−0.7512	0.2065	0.7790
−0.5544	−0.5473	0.7790
0.1968	−0.7538	0.7790
0.7512	−0.2065	0.7790
0.7149	0.3827	0.8109
0.0261	0.8105	0.8109
−0.6889	0.4278	0.8109
−0.7149	−0.3827	0.8109
−0.0261	−0.8105	0.8109
0.6889	−0.4278	0.8109
0.8126	0.0118	0.8127
0.3961	0.7097	0.8127
−0.4166	0.6979	0.8127
−0.8126	−0.0118	0.8127
−0.3961	−0.7097	0.8127
0.4166	−0.6979	0.8127
0.7732	0.2667	0.8179
0.1557	0.8030	0.8179
−0.6175	0.5363	0.8179
−0.7732	−0.2667	0.8179
−0.1557	−0.8030	0.8179
0.6175	−0.5363	0.8179
0.8082	0.1416	0.8205
0.2815	0.7707	0.8205
−0.5267	0.6291	0.8205

TABLE 1k-continued

199 lenslets density of lenslets 0.8388 radius of lenslets 0.0649		
x	y	distance to center
−0.8082	−0.1416	0.8205
−0.2815	−0.7707	0.8205
0.5267	−0.6291	0.8205
0.6794	0.5121	0.8507
−0.1038	0.8444	0.8507
−0.7831	0.3323	0.8507
−0.6794	−0.5121	0.8507
0.1038	−0.8444	0.8507
0.7831	−0.3323	0.8507
0.5550	0.6771	0.8755
−0.3089	0.8192	0.8755
−0.8639	0.1420	0.8755
−0.5550	−0.6771	0.8755
0.3089	−0.8192	0.8755
0.8639	−0.1420	0.8755
0.9015	0.2319	0.9309
0.2499	0.8967	0.9309
−0.6516	0.6648	0.9309
−0.9015	−0.2319	0.9309
−0.2499	−0.8967	0.9309
0.6516	−0.6648	0.9309
0.9301	0.0967	0.9351
0.8627	0.3608	0.9351
0.8044	0.4768	0.9351
0.6799	0.6419	0.9351
0.4959	0.7928	0.9351
0.3813	0.8538	0.9351
0.1189	0.9275	0.9351
−0.0108	0.9350	0.9351
−0.2159	0.9098	0.9351
−0.4386	0.8258	0.9351
−0.5488	0.7571	0.9351
−0.7438	0.5667	0.9351
−0.8151	0.4582	0.9351
−0.8959	0.2679	0.9351
−0.9345	0.0330	0.9351
−0.9301	−0.0967	0.9351
−0.8627	−0.3608	0.9351
−0.8044	−0.4768	0.9351
−0.6799	−0.6419	0.9351
−0.4959	−0.7928	0.9351
−0.3813	−0.8538	0.9351
−0.1189	−0.9275	0.9351
0.0108	−0.9350	0.9351
0.2159	−0.9098	0.9351
0.4386	−0.8258	0.9351
0.5488	−0.7571	0.9351
0.7438	−0.5667	0.9351
0.8151	−0.4582	0.9351
0.8959	−0.2679	0.9351
0.9345	−0.0330	0.9351

While exemplary embodiments are described above, it is not intended that these embodiments describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention. Additionally, the features of various implementing embodiments may be combined to form further embodiments of the invention.

What is claimed is:

1. A light collector adapted to collect light from a plurality of light sources, the light collector comprising:

a plurality of lenslets adapted to collect light from the light sources and adapted to convert the collected light into a plurality of light beams so that the plurality of light beams propagate along an optical axis, wherein each lenslet of the plurality of lenslets comprises an entrance surface where the light enters the lenslet and

an exit surface where the light exits the lenslet, the plurality of lenslets are arranged in a dense pattern, wherein the plurality of lenslets comprise a plurality of outermost adjacent lenslets located along an outer circular boundary, wherein each of the plurality of outermost adjacent lenslets has a same diameter as that of the other plurality of outermost adjacent lenslets, and has a same radial distance to a center of the light collector, wherein each of the plurality of outermost adjacent lenslets contacts two other outermost adjacent lenslets and at least one inner lenslet located inside the plurality of outermost adjacent lenslets, and wherein the dense pattern has been obtained by optimizing a packaging density defined by a ratio of a sum of areas of circular cross sections of the plurality of lenslets and an area enclosed or defined by the outer circular boundary, wherein the plurality of outermost adjacent lenslets comprise at least 12 outermost lenslets and that the packaging density is at least 0.79,

a first group of lenslets of the plurality of lenslets located inside the plurality of outermost adjacent lenslets is arranged on a first annular ring; and

a second group of lenslets of the plurality of lenslets located inside the plurality of outermost adjacent lenslets is arranged on a second annular ring,

wherein a diameter of each of the plurality of lenslets is the same for the first group of lenslets and the second group of lenslets,

wherein a difference in length of a first lenslet of the first group of lenslets on the first annular ring to the center of the light collector and a first lenslet of the second group of lenslets on the second annular ring to the center of the light collector is less than a half of the diameter of each of the plurality of lenslets, and

wherein the dense pattern is a non-hexagonal pattern.

2. The light collector of claim 1 wherein the packaging density is less than 0.88.

3. The light collector of claim 1 wherein the light collector comprises at least 20 lenslets.

4. The light collector of claim 1 wherein a number of the plurality of lenslets is within one of the following intervals: [36, 38]; [54, 55]; [60,61]; [82, 87]; [113,122]; [148, 157]; [198, 201]; [234, 254]; [264, 276]; [291, 302]; [327, 337]; [498, 425]; [478, 501]; [560, 583]; [630, 660]; [718,747]; [779,789]; [817, 847]; [910, 913]; [927, 933]; [1124, 1138]; [1231,1244]; [1415,1446]; and [1468,1500].

5. The light collector of claim 1 wherein a number of the plurality of lenslets is equal to any one of: 37, 55, 61, 85, 91, 121, 151, 199, 219, 235, 241, 270, 295, 301, 331, 349, 421, 481, 499, 528, 565, 631, 637, 649, 690, 745, 783, 847, 913, 931, 1003, 1015, 1027, 1039, 1045, 1092, 1133, 1180, 1201, 1236, 1244, 1278, 1304, 1379, 1420, 1427, 1436, 1446, and 1491.

6. The light collector of claim 1 wherein each of the plurality of outermost adjacent lenslets are in contact with two adjacent other outermost located lenslets.

7. The light collector of claim 1 wherein the plurality of lenslets is arranged in an invariant pattern and wherein the invariant pattern is invariant under a 60 degrees rotation.

8. The light collector of claim 1 wherein:

each lenslet of the plurality of lenslets defines a disc corresponding to a substantial uniform circular cross section of the lenslet, wherein each disc of each lenslet include a same diameter, and

wherein the dense pattern has been obtained by optimizing a packaging density defined by a ratio of the sum of areas of the discs and an area of a container disc circumscribing the discs.

9. The light collector of claim **1** wherein at least one of the plurality of lenslets have been omitted.

10. An illumination device comprising:

a plurality of light sources;

a light collector according to claim **1**;

an optical gate arranged along the optical axis; and

an optical projecting system adapted to collect at least a part of the plurality of light beams and adapted to image the optical gate at a distance along the optical axis.

11. The illumination device of claim **10**, wherein the plurality of light sources are arranged on a flat plane.

12. The light collector of claim **1** further comprising an imaging lens that includes a circular aperture.

13. A method of providing a light collector adapted to collect light from a plurality of light sources, wherein the light collector comprises a plurality of lenslets adapted to collect light from the plurality of light sources and adapted to convert the collected light into a plurality of light beams so that the plurality of light beams propagate along an optical axis, wherein each lenslet of the plurality of lenslets comprise an entrance surface where the light enters the lenslet and an exit surface where the light exits the lenslet, and wherein each lenslet of the plurality of lenslets has a substantial uniform circular cross section of the lenslet, the method comprising:

arranging the lenslets in a dense pattern, wherein the plurality of lenslets comprise a plurality of outermost lenslets located along an outer circular boundary, wherein each of the plurality of outermost lenslets has a same diameter as that of the other plurality of outermost lenslets, and has a same radial distance to a center of the light collector, wherein each of the plurality of outermost lenslets contacts two other outermost lenslets and at least one inner lenslet located inside the plurality of outermost lenslets,

optimizing a packaging density defined by a ratio of a sum of areas of circular cross sections of the plurality of lenslets and an area enclosed or defined by the outer circular boundary,

providing at least 12 outermost lenslets,

optimizing the packaging density to at least 0.79,

arranging a first group of lenslets of the plurality of lenslets located inside the plurality of outermost lenslets on a first annular ring; and

arranging a second group of lenslets of the plurality of lenslets located inside the plurality of outermost lenslets on a second annular ring,

wherein a diameter of each of the plurality of lenslets is the same for the first group of lenslets and the second group of lenslets,

wherein a difference in length of a first lenslet of the first group of lenslets on the first annular ring to the center of the light collector and a first lenslet of the second group of lenslets on the second annular ring to the center of the light collector is less than a half of the diameter of each of the plurality of lenslets,

wherein the dense pattern is a non-hexagonal pattern.

14. The method of claim **13** further comprising selecting a number of the plurality of lenslets from one of the following intervals: [36, 38]; [54, 55]; [60,61]; [82, 87];

[113,122]; [148, 157]; [198, 201]; [234, 254]; [264, 276]; [291, 302]; [327, 337]; [498, 425]; [478, 501]; [560, 583]; [630, 660]; [718,747]; [779, 789]; [817, 847]; [910, 913]; [927, 933]; [1124, 1138]; [1231,1244]; [1415,1446]; and [1468,1500].

15. The method of claim **13** further comprising selecting a number of the plurality of lenslets from any one of: 37, 55, 61, 85, 91, 121, 151, 199, 219, 235, 241, 270, 295, 301, 331, 349, 421, 481, 499, 528, 565, 631, 637, 649, 690, 745, 783, 847, 913, 931, 1003, 1015, 1027, 1039, 1045, 1092, 1133, 1180, 1201, 1236, 1244, 1278, 1304, 1379, 1420, 1427, 1436, 1446, and 1491.

16. The method of claim **13** further comprising:

arranging the light collector to collect light from a plurality of light sources and to direct the plurality of light beams through an optical gate; and

arranging an optical projecting system to collect at least a part of the plurality of light beams.

17. A light collector adapted to collect light from a plurality of light sources, the light collector comprising:

a plurality of lenslets adapted to collect light from the light sources and adapted to convert the collected light into a plurality of light beams so that the plurality of light beams propagate along an optical axis, wherein each lenslet of the plurality of lenslets comprises an entrance surface where the light enters the lenslet and an exit surface where the light exits the lenslet, the plurality of lenslets are arranged in a dense pattern, wherein the plurality of lenslets comprise a plurality of outermost adjacent lenslets located along an outer circular boundary, wherein each of the plurality of outermost adjacent lenslets has a same diameter as that of the other plurality of outermost adjacent lenslets, and has a same radial distance to a center of the light collector, wherein each of the plurality of outermost adjacent lenslets contacts two other outermost adjacent lenslets and at least one inner lenslet located inside the plurality of outermost adjacent lenslets, and wherein the dense pattern has been obtained by optimizing a packaging density defined by a ratio of a sum of areas of circular cross sections of the plurality of lenslets and an area enclosed or defined by the outer circular boundary, wherein the plurality of outermost adjacent lenslets comprise at least 12 outermost lenslets and that the packaging density is less than 0.88,

a first group of lenslets of the plurality of lenslets located inside the plurality of outermost adjacent lenslets is arranged on a first annular ring; and

a second group of lenslets of the plurality of lenslets located inside the plurality of outermost adjacent lenslets is arranged on a second annular ring,

wherein a diameter of each of the plurality of lenslets is the same for the first group of lenslets and the second group of lenslets,

wherein a difference in length of a first lenslet of the first group of lenslets on the first annular ring to the center of the light collector and a first lenslet of the second group of lenslets on the second annular ring to the center of the light collector is less than a half of the diameter of each of the plurality of lenslets, and

wherein the dense pattern is a non-hexagonal pattern.

18. The light collector of claim **17** wherein the packaging density is at least 0.79.

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