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(54) RADIATION DETECTION DEVICE

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(57) ABSTRACT

A radiation detection device is provided that is wide in visual field, wide in application range of radiation energy, and which is smaller and lighter in weight as compared to other devices. The device includes a detecting element group has a plurality of detecting elements that detect radiation are three-dimensionally arranged. The detecting element group has a structure with a depletion formed by removing the detecting element at any position from a virtual detecting element group in which the detecting elements are laid out on any virtual surface. The depletion is provided at a position at which a difference of detected values between one detecting element and another detecting element arranged along any direction exhibits different values in a case where the radiation having the direction as an incident direction enters and a case where the radiation having an opposite direction of the direction as an incident direction enters.

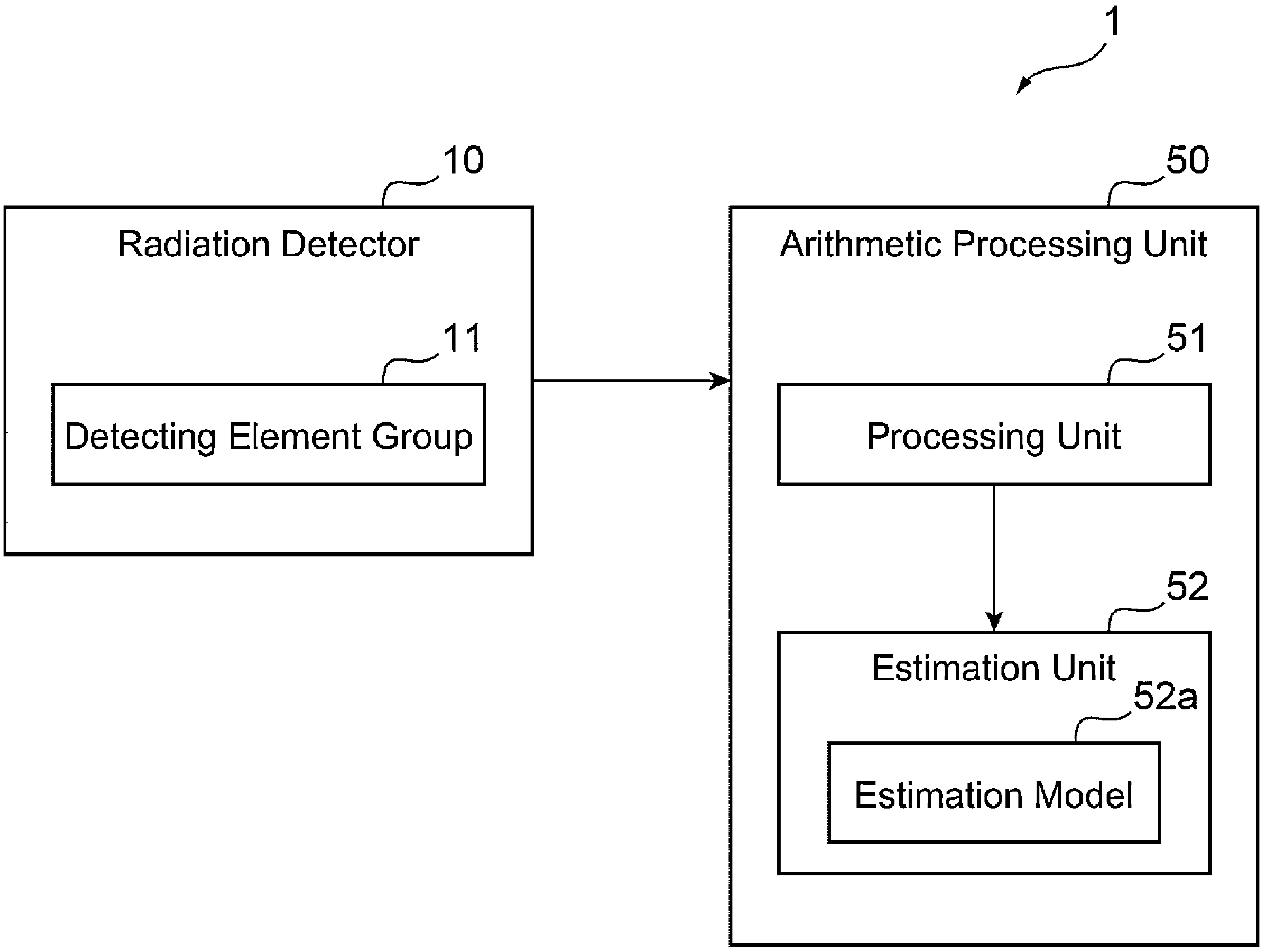


Fig. 1

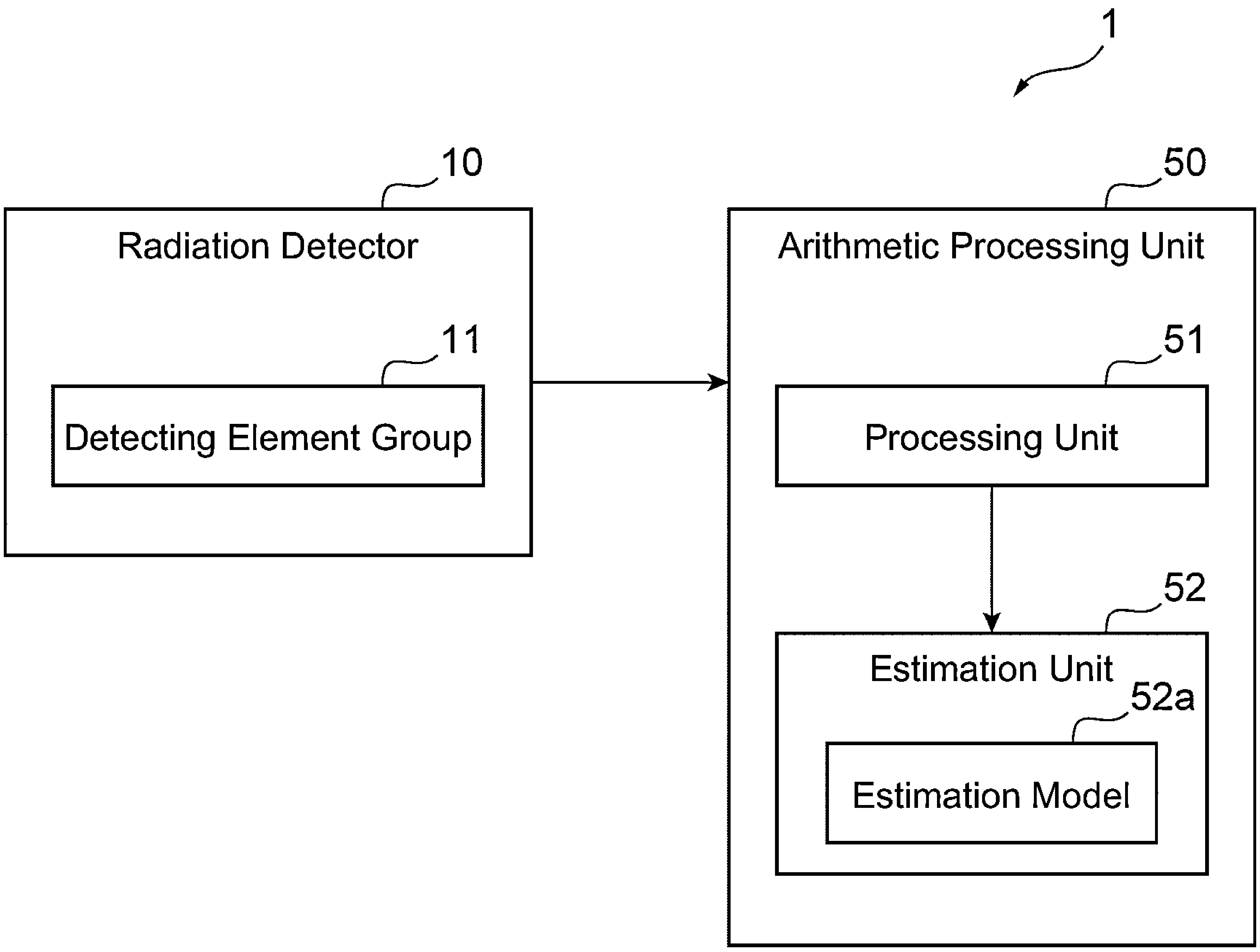

1
10
Radiation Detector
11
Detecting Element Group
50
Arithmetic Processing Unit
51
Processing Unit
52
Estimation Unit
52a
Estimation Model

Fig. 2

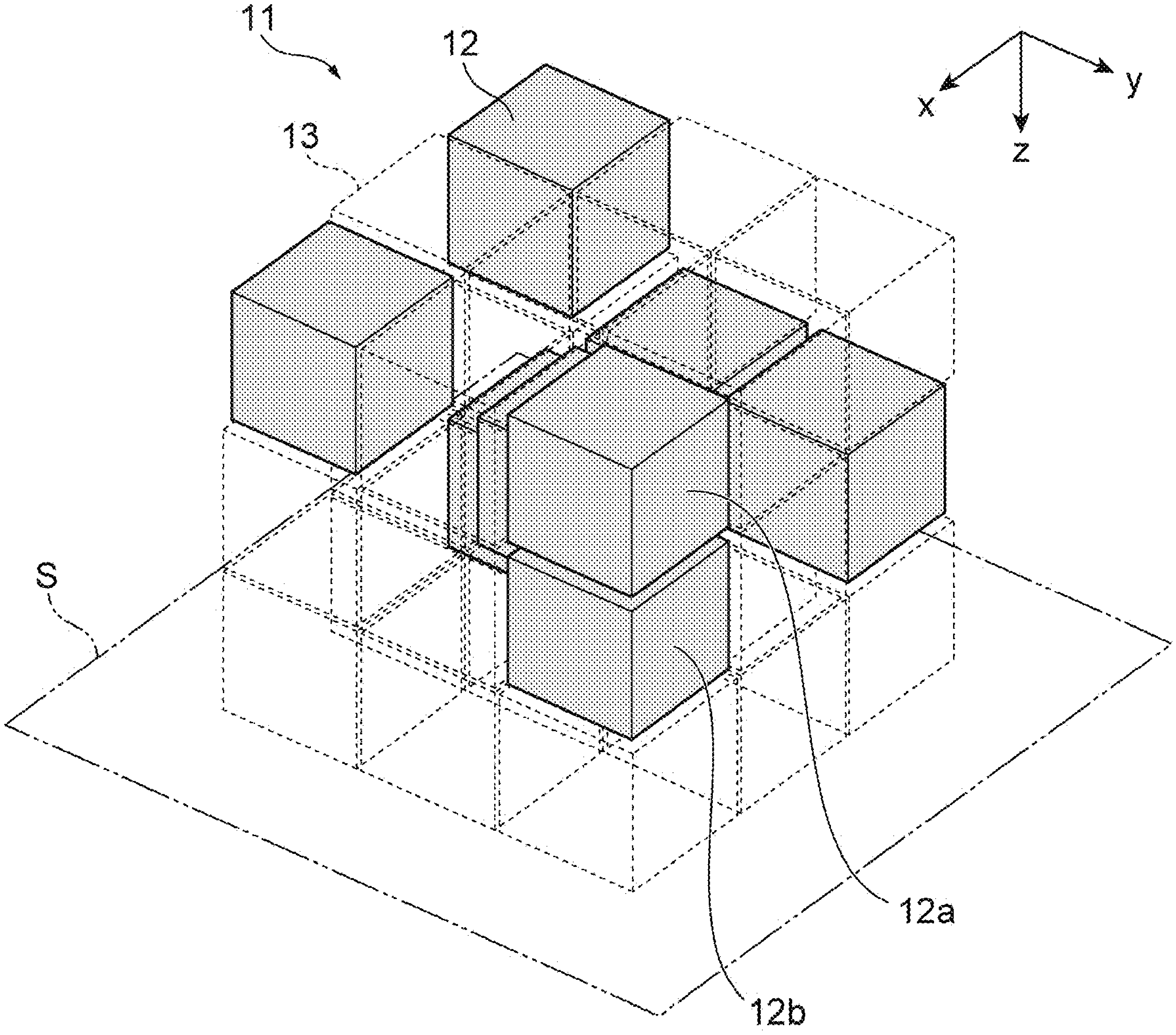


Fig. 3

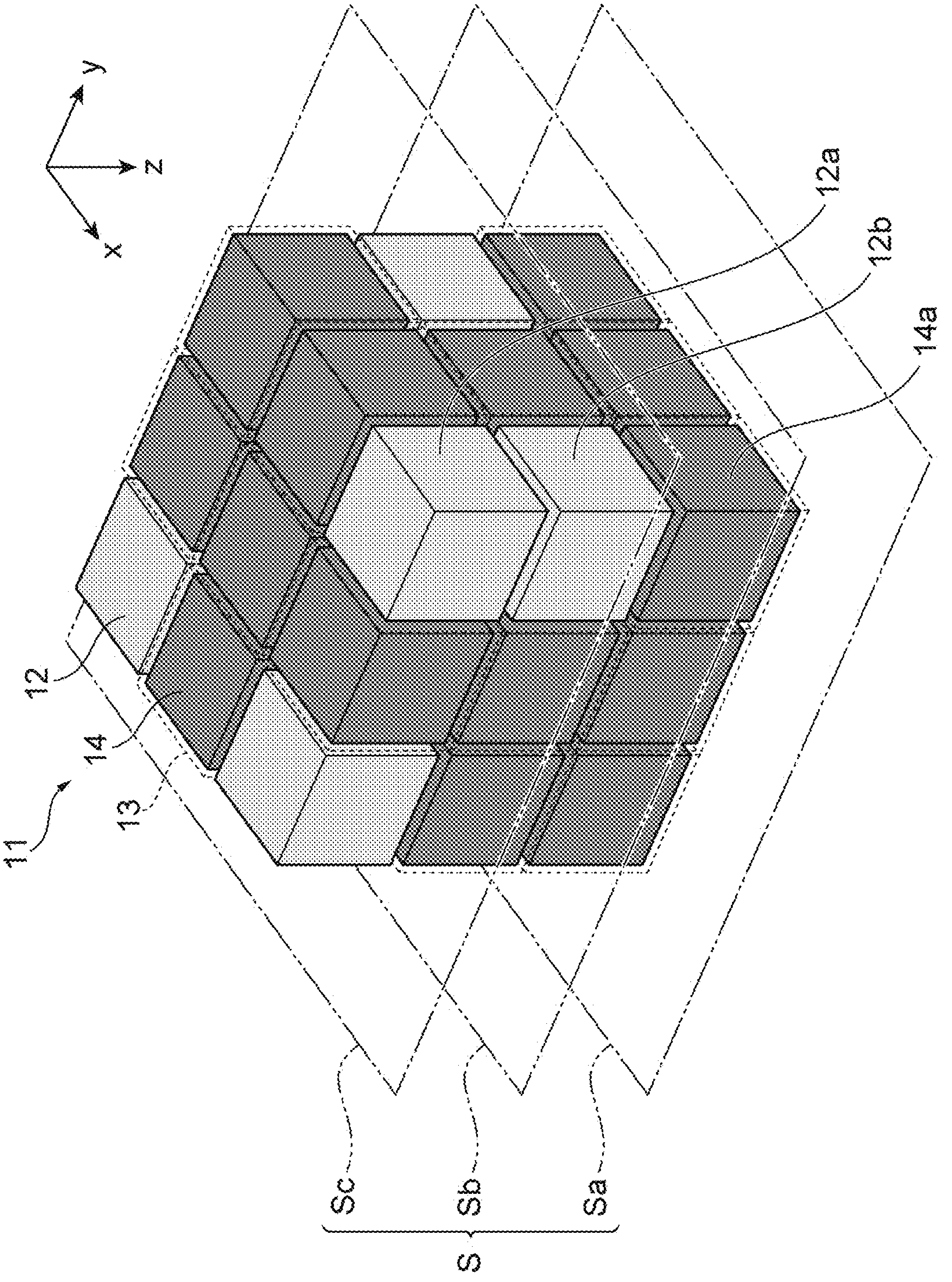


Fig. 4

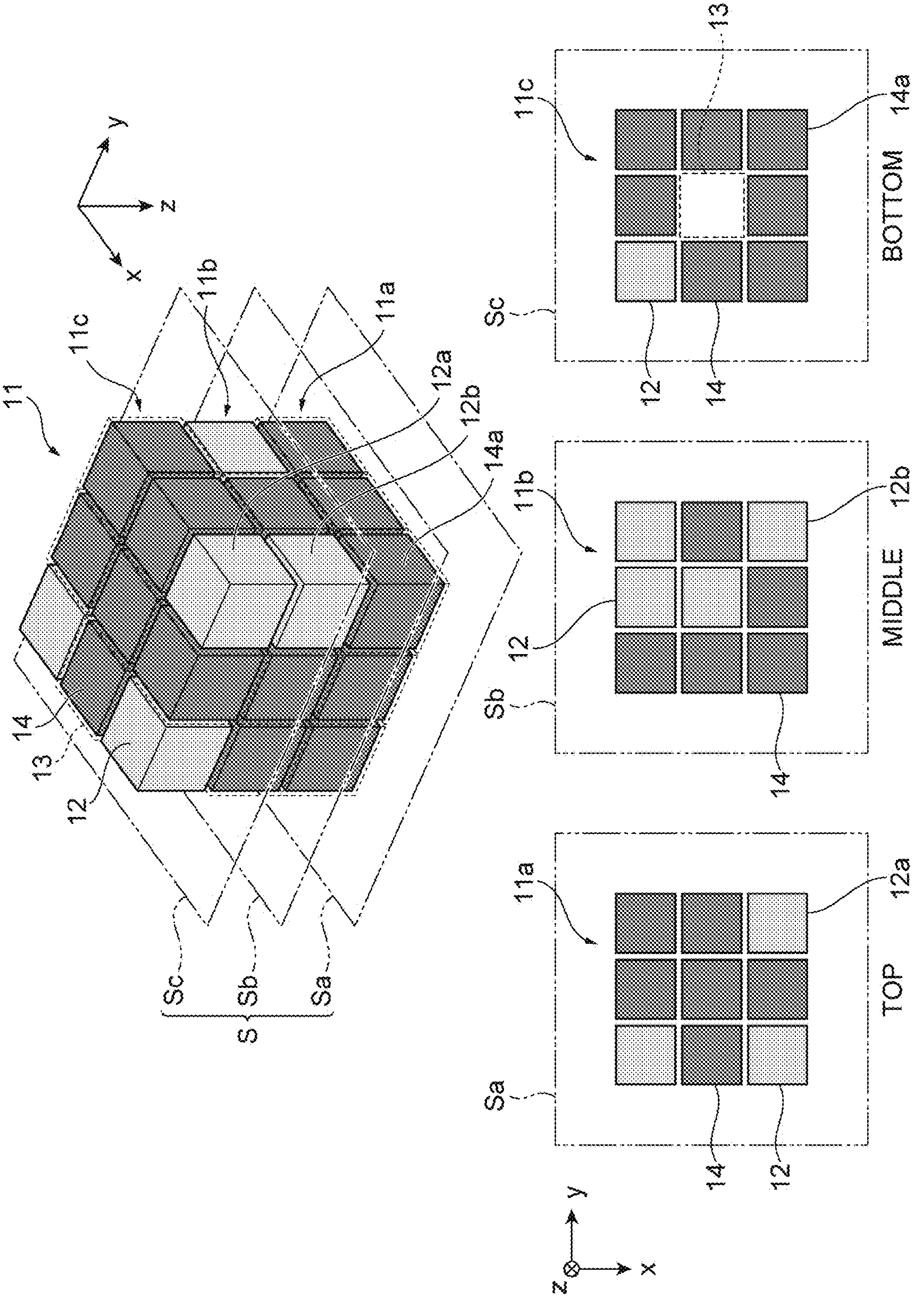

11
11c
11b
11a
12a
12b
14a
14
13
12
Sc
Sb
Sa
S
x
y
z
Sa
11a
12a
14
12
TOP
Sb
11b
12b
12
14
MIDDLE
Sc
11c
13
14a
12
14
BOTTOM
z
y
x

Fig. 5

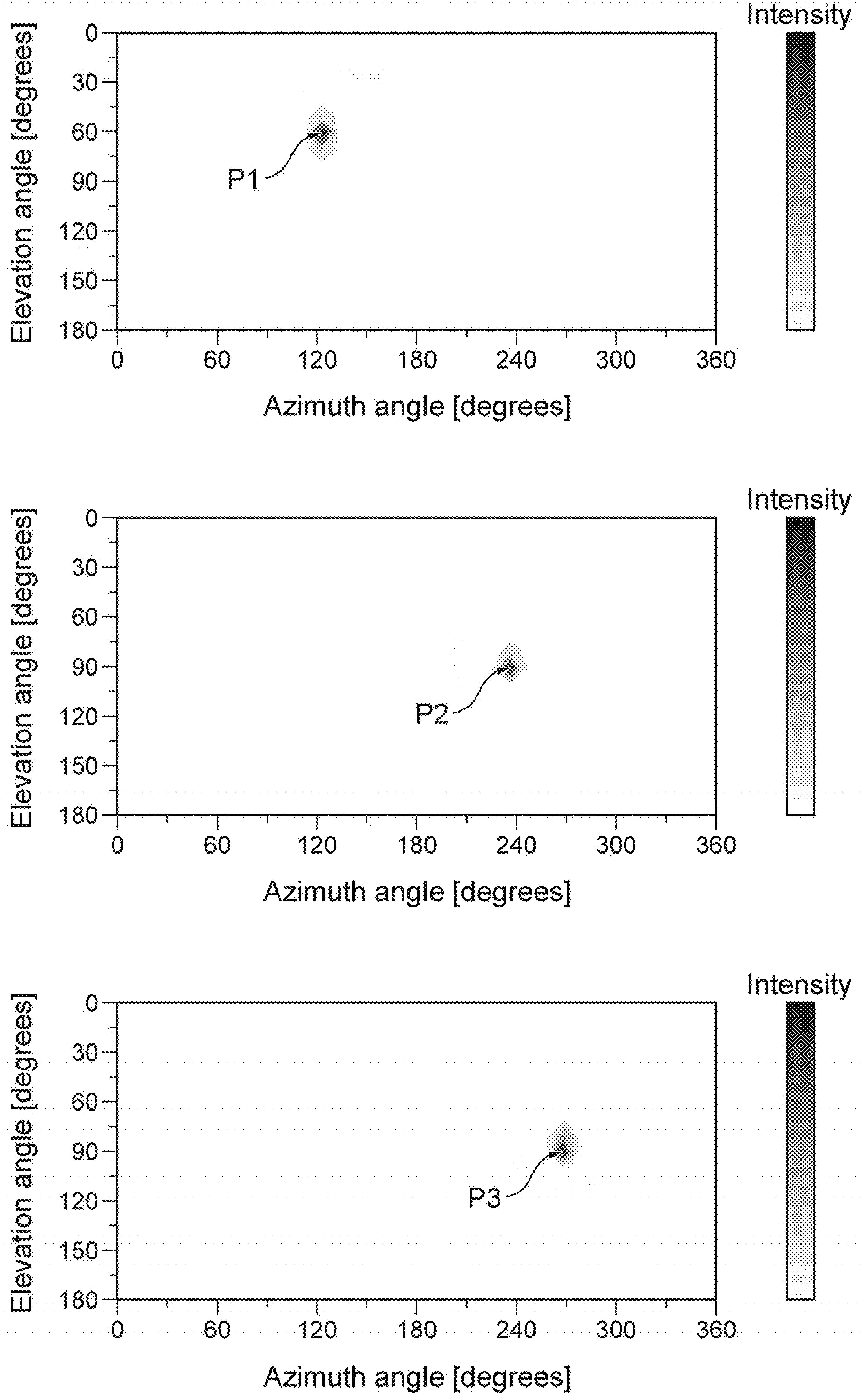
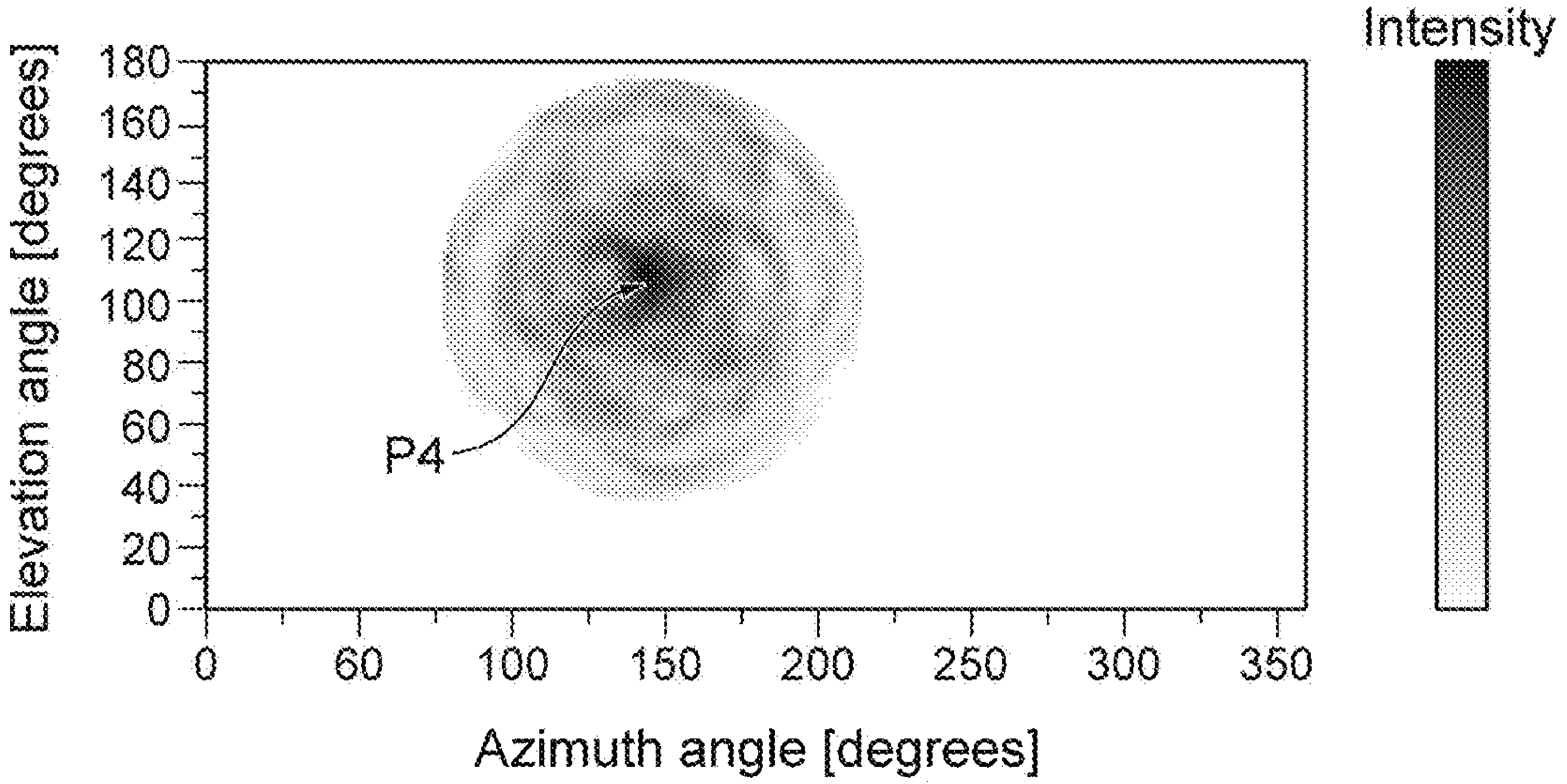

Intensity
Elevation angle [degrees]
0
30
60
90
120
150
180
P1
0
60
120
180
240
300
360
Azimuth angle [degrees]
Intensity
Elevation angle [degrees]
0
30
60
90
120
150
180
P2
0
60
120
180
240
300
360
Azimuth angle [degrees]
Intensity
Elevation angle [degrees]
0
30
60
90
120
150
180
P3
0
60
120
180
240
300
360
Azimuth angle [degrees]

Fig. 6


Intensity
Elevation angle [degrees]
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160
140
120
100
80
60
40
20
0
P4
0
60
100
150
200
250
300
350
Azimuth angle [degrees]

Fig. 7

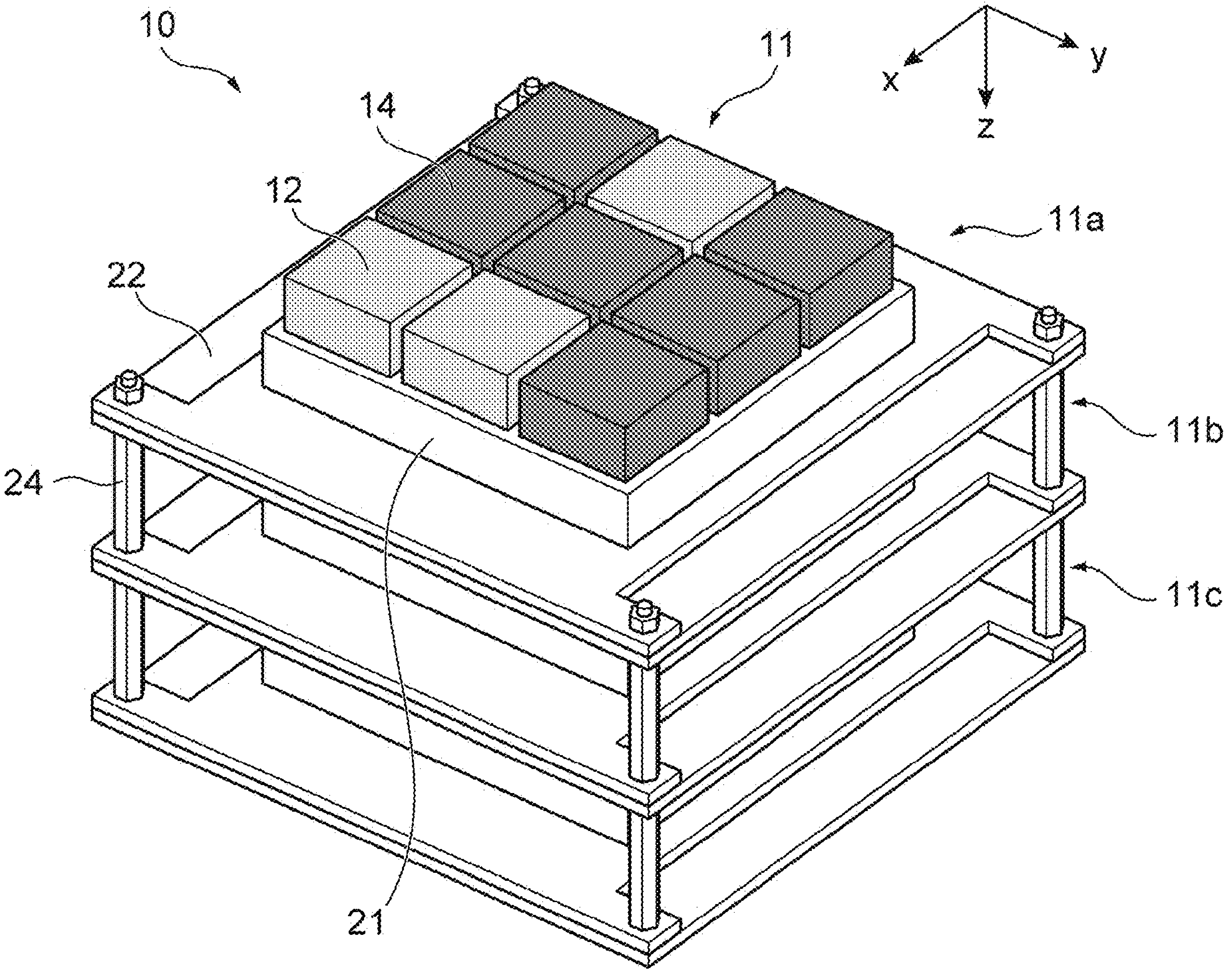


Fig. 8

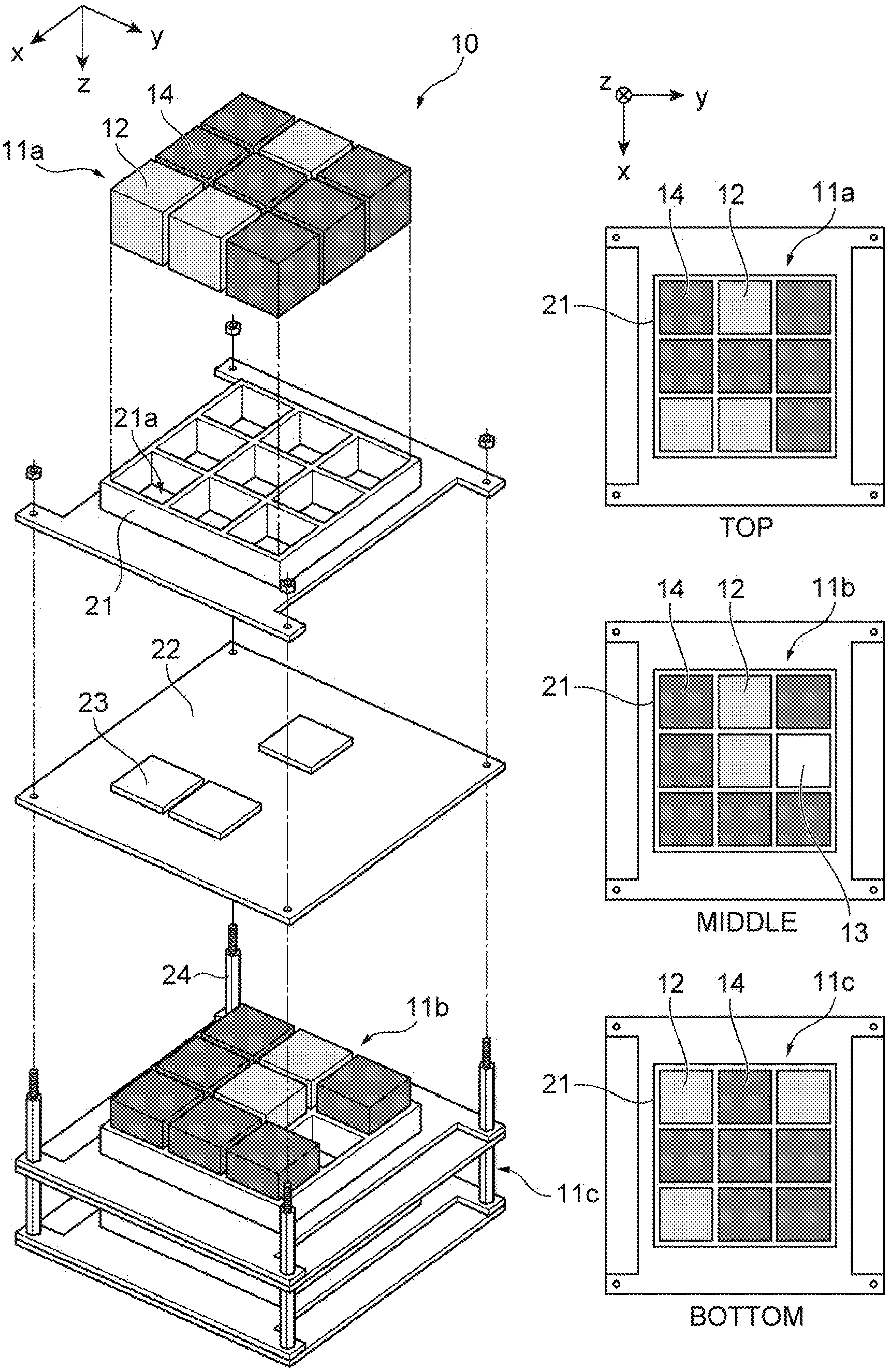
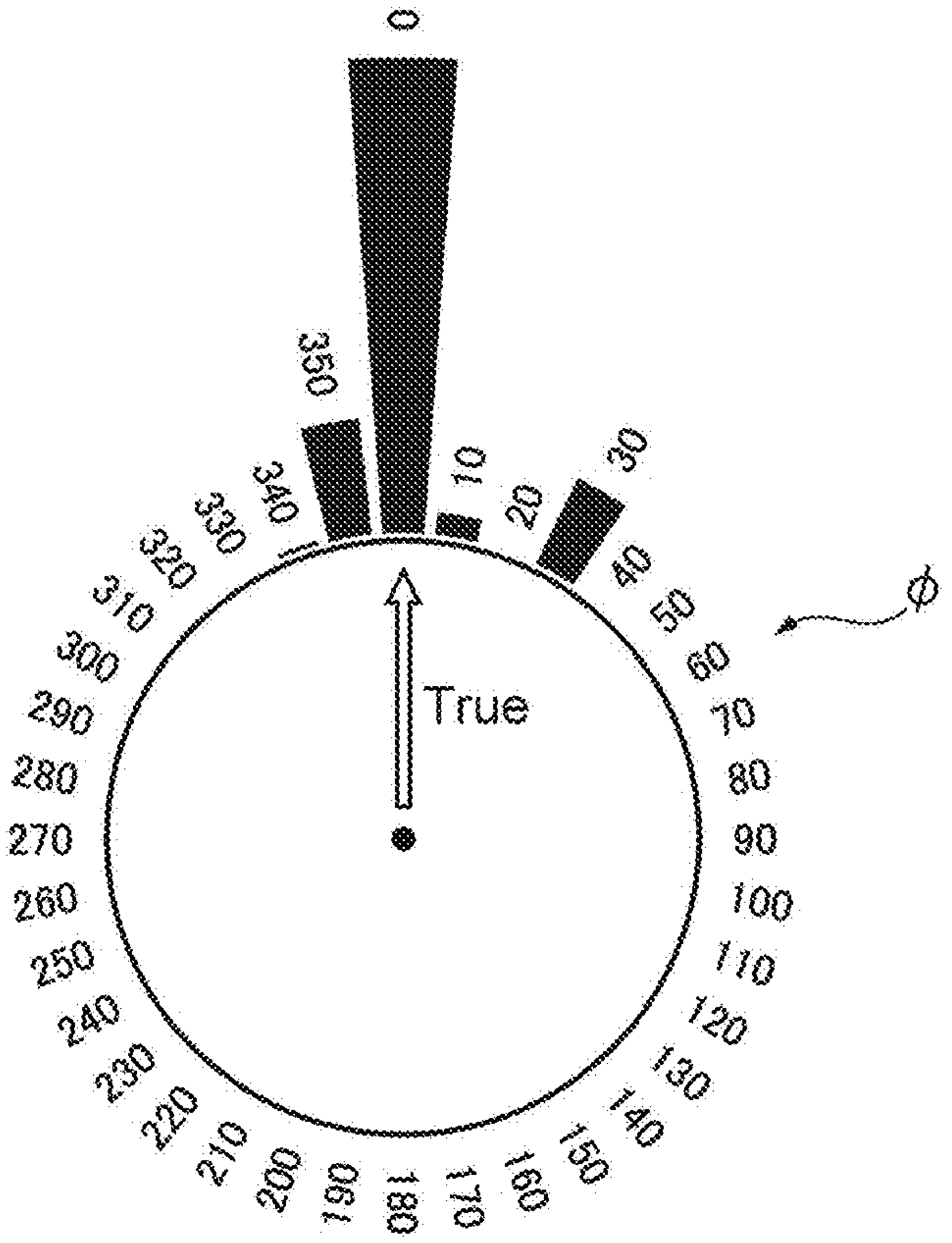
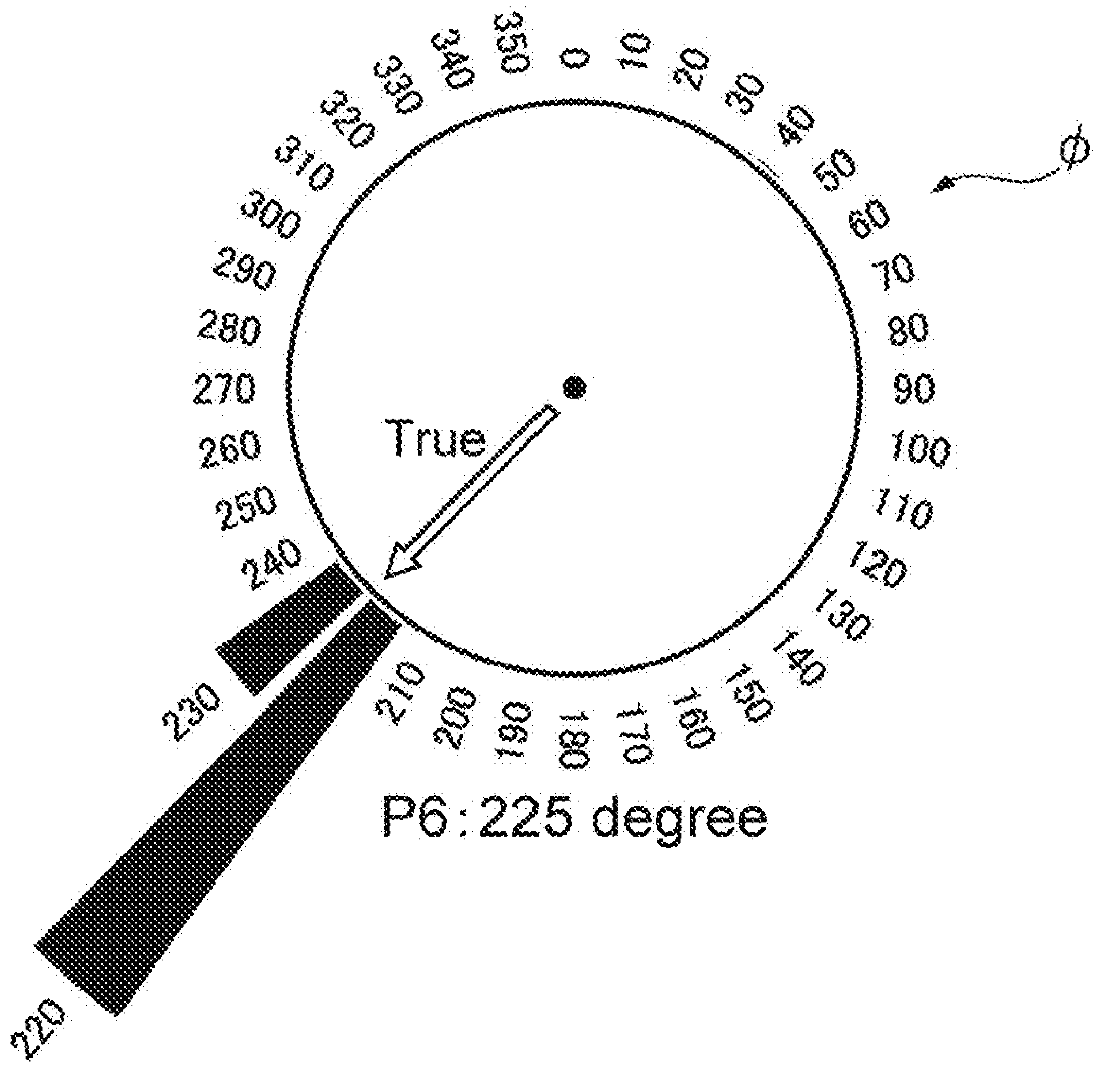

x
y
z
10
14
12
11a
21a
21
22
23
24
11b
11c
z
y
x
14
12
11a
21
TOP
14
12
11b
21
MIDDLE
13
12
14
11c
21
BOTTOM

Fig. 9



P5 : 0 degree



P6:225 degree

Fig. 10

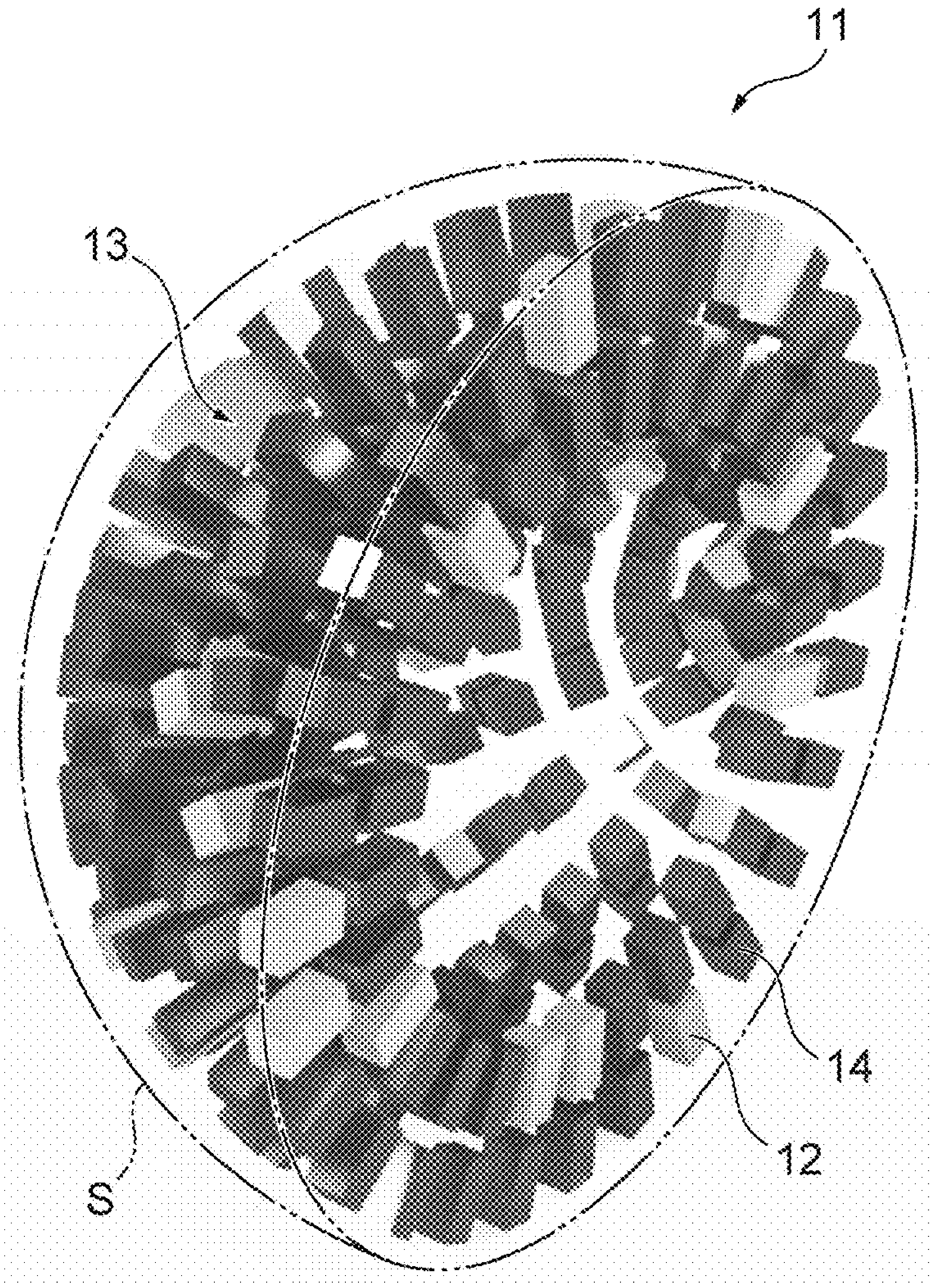


Fig. 11

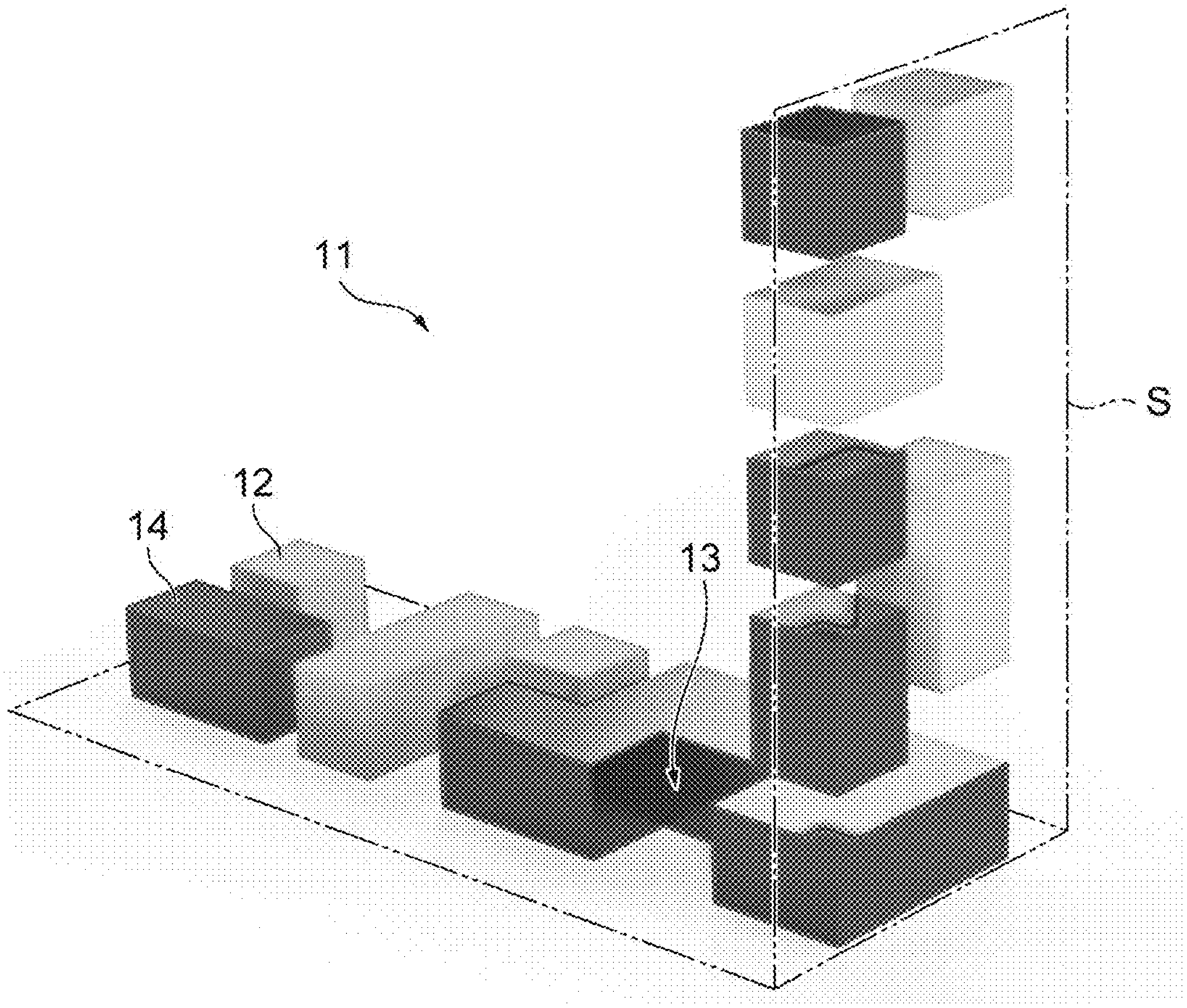
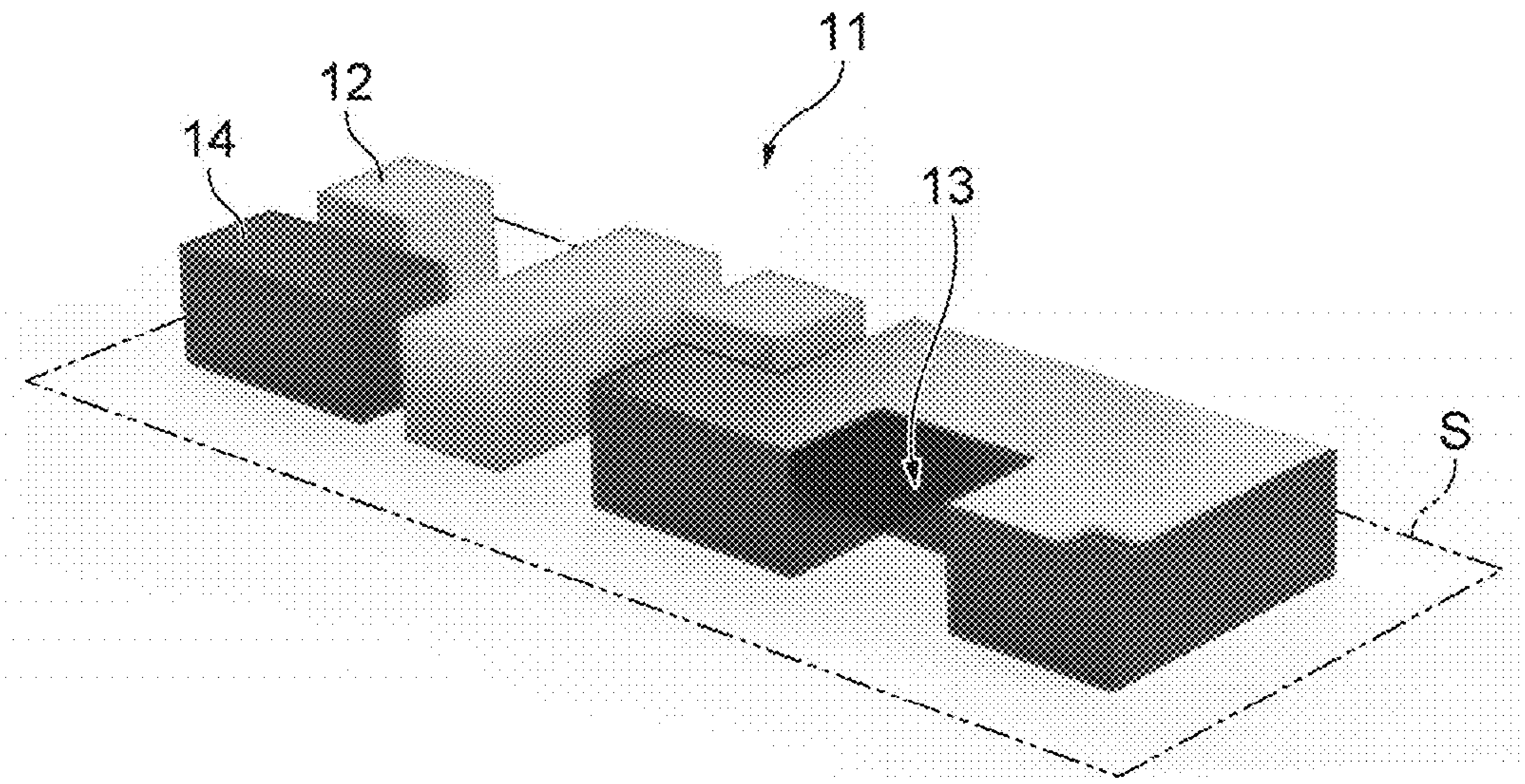


Fig. 12



RADIATION DETECTION DEVICE

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority from Japanese Patent Application No. 2023-007015, filed Jan. 20, 2023, the contents of which are incorporated herein by reference.

TECHNICAL FIELD

[0002] The present invention relates to a radiation detection device.

BACKGROUND OF THE INVENTION

[0003] Radiation detection devices such as a gamma-ray imager that detects and visualizes radiation, such as a gamma ray are known. Typical examples include a Compton camera, a pinhole camera, or a camera of coded mask type.

[0004] The Compton camera requires ONE to match detection timings of signals (make a coincidence) between two different detecting elements. Therefore, application of the Compton camera is difficult when the signal detection rate is too high to keep up the process. Since the Compton camera requires a considerably large number of detecting elements, the circuit is complicated, and the price is high. For the Compton camera, a product with a visual field in which a solid angle is in a range of 2π sr or less in the front of the camera is common, and when the product is used, it is necessary to perform a measurement multiple times or use a plurality of Compton cameras for radiation detection and imaging in all directions (solid angle is 4π sr).

[0005] Since the pinhole camera requires a heavy and large-sized shield of lead, tungsten, or the like, the weight of the device exceeds tens of kilograms. Carrying the pinhole camera is not easy, and the pinhole camera it is not practical to mount it to a small-sized search robot. Furthermore, since the pinhole camera detects only radiation that has passed through a small pinhole formed at the shield, the detection sensitivity is low, and the visual field is narrow.

[0006] For the coded mask type camera, when events of high energy gamma ray that have passed through the coded mask increase to substantially deteriorate the imaging accuracy, the detectable energy range of radiation is limited. Further, in an environment in which radiation enters from directions other than the front of the detecting element, since the noise increases, the coded mask type camera is not appropriate for use. The coded mask type camera also has a narrow visual field when compared with the Compton camera and the pinhole camera and is not appropriate also for application in radiation detection and imaging in a wide region.

SUMMARY OF THE INVENTION

[0007] However, while the radiation detection devices disclosed above can ensure the visual field in all directions, a large number of detecting elements is still necessary, and the weight of the device is heavy. Therefore, the radiation detection devices disclosed above have room for improvement when compared similarly to a conventional radiation detection device, such as a Compton camera.

[0008] The present invention has been made in consideration of the circumstances described above and provides a novel radiation detection device that is wide in visual field, wide in application range of radiation energy, and a device which is smaller and lighter in weight.

[0009] To solve the above-described problem, a radiation detection device of the present invention is one that includes a detecting element group in which a plurality of detecting elements that detect radiation are three-dimensionally arranged. The detecting element group has a structure provided with a depletion formed by removing the detecting element at any position from a virtual detecting element group in which the detecting elements are laid out on any virtual surface. The depletion is provided at a position at which a difference of detected values between one detecting element and another detecting element arranged along any direction exhibits different values in a case where the radiation having the direction as an incident direction enters and a case where the radiation having an opposite direction of the direction as an incident direction enters.

[0010] The present invention can provide a novel radiation detection device that is wide in visual field, wide in application range of radiation energy, and a device which is smaller and lighter in weight.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a diagram illustrating a configuration of a radiation detection device of the embodiment;

[0012] FIG. **2** is a diagram describing a structure of a detecting element group illustrated in FIG. **1**;

[0013] FIG. **3** is a diagram describing a structure of the detecting element group in which shielding members are provided at depletions illustrated in FIG. **2**;

[0014] FIG. **4** is a diagram describing a detailed structure of the detecting element group illustrated in FIG. **3**;

[0015] FIG. **5** is a diagram illustrating simulation results of estimation of a source location by the radiation detection device including the detecting element group illustrated in FIG. **3** and FIG. **4**;

[0016] FIG. **6** is a diagram illustrating a result of estimation of a source location by a conventional radiation detection device;

[0017] FIG. **7** is a perspective view illustrating an example of a radiation detector;

[0018] FIG. **8** is an exploded perspective view of the radiation detector illustrated in FIG. **7**;

[0019] FIG. **9** is a diagram illustrating experimental results of an estimation of the source location by the radiation detector illustrated in FIG. **7** and FIG. **8**;

[0020] FIG. **10** is a diagram describing an example of another structure of the detecting element group;

[0021] FIG. **11** is a diagram describing an example of another structure of the detecting element group; and

[0022] FIG. **12** is a diagram describing an example of another structure of the detecting element group.

DETAILED DESCRIPTION

[0023] The following describes embodiments of the present invention with reference to the drawings. Configurations to which the same reference numerals are attached in the respective embodiments have similar functions in the respective embodiments insofar as they are not especially mentioned, and their explanations will be omitted.

[0024] FIG. **1** is a diagram illustrating a configuration of a radiation detection device **1** of the embodiment. FIG. **2** is a diagram describing a structure of a detecting element group **11** illustrated in FIG. **1**.

[0025] The radiation detection device **1** is a device that detects and visualizes radiation. The radiation detection device **1** is applicable to a wide radiation energy range from an X-ray of about several keV to a gamma ray of tens of MeV. Further, the radiation detection device **1** is applicable to environments of various dose rates from a low-dose field of about several uSv/h or less to an ultra-high dose field of several Sv/h. For example, the radiation detection device **1** is applicable to a gamma-ray imager used for the investigation of radioactive contamination inside the building of Fukushima Daiichi Nuclear Power Plant, a gamma-ray imager used at an ultra-high dose field, such as a pressure vessel, an X-ray or gamma-ray imager installed in an astronomy satellite, a gamma-ray imager used for an investigation of radioactive contamination in an outdoor environment, a gamma-ray imager installed in medical equipment for radiation therapy, and a detector for nuclear security in a large-scale event or the like.

[0026] The radiation detection device **1** includes a radiation detector **10** provided with a detecting element group **11** including a plurality of detecting elements **12** that detect radiation, and an arithmetic processing unit **50** that is connected to the radiation detector **10** and processes a detection result of the radiation detector **10**.

[0027] The detecting element **12** is not specifically limited insofar as it is an element that can detect radiation as a detection target. When the radiation as the detection target is a gamma ray, for the detecting element **12**, various elements, such as a scintillator, a semiconductor-type detecting element, or an integration-type detecting element, may be considered. In this embodiment, a case where the radiation as the detection target is a gamma ray, and the detecting element **12** is a cubic scintillator will be described.

[0028] The detecting element group **11** includes a plurality of the detecting elements **12**. The plurality of detecting elements **12** constituting the detecting element group **11** are three-dimensionally arranged. The detecting element group **11** has a structure provided with a depletion **13** (space) formed by removing the detecting element **12** at any position from a virtual detecting element group in which the detecting elements **12** are laid out on any virtual surface S. For example, FIG. **2** illustrates the detecting element group **11** in which an outer shape of the detecting element group **11** is formed in a cubic shape. FIG. **2** illustrates an outer surface in the bottom side along an xy-plane as the virtual surface S. In the example of FIG. **2**, only one detecting element **12** is disposed for the virtual surface S of the outer surface in the bottom side along the xy-plane, and the detecting elements **12** are not uniformly laid out on the virtual surface S. That is, in the example of FIG. **2**, it can be understood that the eight detecting elements **12** are removed from the virtual detecting element group in which the nine detecting elements **12** are laid out in a square shape on the virtual surface S of the outer surface in the bottom side along the xy-plane, thus forming the eight depletions **13**.

[0029] While only the outer surface in the bottom side along the xy-plane is illustrated as the virtual surface S in the example of FIG. **2**, the virtual surface S is defined for the surface other than this outer surface. Although not illustrated in the example of FIG. **2**, an outer surface in the top side along the xy-plane, a surface passing between a detecting element **12***a* and a detecting element **12***b* along the xy-plane are also defined as the virtual surface S. The virtual surface S can be appropriately defined insofar as the surface is an outer surface of a solid forming the outer shape of the detecting element group **11**, or a surface intersecting with the solid. The number of the virtual surfaces S can also be appropriately defined.

[0030] The depletion **13** is provided at a position at which a difference of detected values between one detecting element **12***a* and the other detecting element **12***b* arranged along any direction intersecting with the outer shape of the detecting element group **11** exhibits different values in a case where the radiation enters from the direction and a case where the radiation enters from an opposite direction of the direction. In the example of FIG. **2**, the difference of the detected values between the one detecting element **12***a* and the other detecting element **12***b* arranged along a +z-axis direction intersecting with the outer shape of the detecting element group **11** exhibits different values in the case where the radiation having the +z-axis direction as the incident direction enters the detecting element group **11** and the case where the radiation having the −z-axis direction, which is the opposite direction of the +z-axis direction, as the incident direction enters the detecting element group **11**.

[0031] This allows the detecting element group **11** to have a relative positional relation between a plurality of detecting elements **12** in any incident direction of the radiation as positional relations different in all directions (solid angle is 4πsr). Accordingly, in the detecting element group **11**, an intensity distribution of the radiation (specifically, intensity distribution of the radiation flux) in the detecting element group **11** obtained from the respective detected values of the plurality of detecting elements **12** can be provided as distributions different in all directions. In other words, the radiation detection device **1** can actively generate the inclination of the radiation flux intensity that differs corresponding to the radiation incident direction in the detecting element group **11**. In the example of FIG. **2**, the radiation intensity distribution in the detecting element group **11** when the radiation having the +z-axis direction as the incident direction is detected is a distribution different from the radiation intensity distribution in the detecting element group **11** when the radiation having the −z-axis direction as the incident direction is detected.

[0032] The radiation detection device **1** uses the radiation intensity distribution in the detecting element group **11** that differs corresponding to the radiation incident direction to estimate a source location of the radiation. The radiation detection device **1** preliminarily stores information in which the direction from which the radiation enters is associated with the distribution that the radiation intensity distribution in the detecting element group **11** exhibits, and estimates the radiation source location from the radiation intensity distribution acquired in the actual measurement.

[0033] Specifically, the arithmetic processing unit **50** of the radiation detection device **1** includes a processing unit **51** that acquires a spatial intensity distribution of the radiation in the detecting element group **11** based on the respective detected values of the plurality of detecting elements **12**, and an estimation unit **52** that estimates the source location of the radiation based on the acquisition result of the radiation intensity distribution. The arithmetic processing unit **50** includes a CPU, a ROM, a RAM, and the like, and the CPU executes programs stored in the ROM to achieve various kinds of functions of the radiation detection device **1** including the processing unit **51** and the estimation unit **52**. The processing unit **51** may be included in the radiation detector **10**.

[0034] The estimation unit **52** may include an estimation model **52***a* for estimating the source location from the acquisition result of the intensity distribution. The estimation model **52***a* is a model preliminarily generated through a machine learning based on training data in which the intensity distribution acquired for each incidence angle of the radiation to the detecting element group **11** (that is, each radiation incident the direction) is associated with the source location at the acquisition of the intensity distribution.

[0035] The method of the machine learning may be unfolding, neural network, or the like. The unfolding is an inverse calculation method often used in the technical field of radiation detection.

[0036] Here, the following formula (1) can be assumed to be satisfied with a matrix R as a response function of the radiation detector **10**, a matrix W as a weighting function as a target to be obtained, and a matrix S as an acquisition result of the intensity distribution.

$$S = RW \tag{1}$$

[0037] Since the response function R is generally a non-normal matrix, an inverse matrix cannot be defined. Therefore, a weighting function W to minimize an objective function σ indicated in the following formula (2) is searched. In this embodiment, the matrix S corresponds to the intensity distribution of the radiation flux as the acquisition result. The matrix R corresponds to a pattern of the radiation flux intensity of each incidence angle of the radiation. The matrix W corresponds to the intensity of each incidence angle.

$$\sigma = (S - RW)^2 \tag{2}$$

[0038] Thus, the radiation detection device **1** can estimate the radiation source location using the radiation intensity distribution that differs corresponding to the radiation incident direction in the detecting element group **11**. Therefore, regardless of the simple configuration of the radiation detector **10**, the radiation source location can be estimated in all directions. Further, the radiation detection device **1** can accurately estimate the radiation source location by the use of the estimation model **52***a* generated through the machine learning regardless of the simple configuration of the radiation detector **10**.

[0039] FIG. **3** is a diagram describing a structure of the detecting element group **11** in which shielding members **14** are provided at the depletions **13** illustrated in FIG. **2**. FIG. **4** is a diagram describing a detailed structure of the detecting element group **11** illustrated in FIG. **3**.

[0040] As illustrated in FIG. **3** and FIG. **4**, the depletion **13** may be provided with the shielding member **14** that shields against the radiation. The shielding member **14** does not need to be provided to every depletion **13**, and can be appropriately provided depending on the energy range or a dose rate of the radiation as a detection target. That is, at least a part of the depletions **13** (at least one depletion **13**) may be provided with the shielding member **14**. The shielding member **14** may be formed in a cubic shape similar to the detecting element **12**. When the radiation as the detection target is a neutron ray, the shielding member **14** is preferably made of water, boron, or the like as a light element material. When the radiation as the detection target is highly penetrating radiation, such as a gamma ray or an X-ray, the shielding member **14** is preferably made of lead, tungsten, or the like as a heavy element material. That is, for the arrangement, the shape, and the selection of material of the shielding member **14**, the change of design can be appropriately made in terms of actively generating the inclination of radiation flux intensity that differs corresponding to the radiation incident direction in the detecting element group **11**.

[0041] For the volume or the density of the detecting element **12**, the change of design can be appropriately made as well. For example, by changing the design to make a difference in volume or density between the one detecting element **12***a* and the other detecting element **12***b* in the radiation incident direction, the inclination of the radiation flux intensity can be actively generated in the detecting element group **11**. For the type of the detecting element **12**, the change of design can be appropriately made as well. For example, by changing the design to make a difference in radiation detection sensitivity between the one detecting element **12***a* and the other detecting element **12***b*, for example, having the one detecting element **12***a* as a beta-ray detecting element and the other detecting element **12***b* as an alpha-ray detecting element, the inclination of radiation flux intensity can be actively generated in the detecting element group **11**.

[0042] With the shielding member **14** provided to the depletion **13**, the radiation detection device **1** can increase the difference of the detected values between the plurality of detecting elements **12** in the detecting element group **11**. This allows the radiation detection device **1** to give the difference increased corresponding to the radiation incident direction to the radiation intensity distribution in the detecting element group **11** acquired from the respective detected values of the plurality of detecting elements **12**. Accordingly, the radiation detection device **1** can accurately estimate the radiation incident direction, and can accurately estimate the radiation source location. Especially, in a high-dose field, such as an inside of the building of Fukushima Daiichi Nuclear Power Plant, not only the signal detection rate of the detecting element **12** is too high to keep up the process (causes piling up), but also the radiation passing through the detecting element **12** does not allow the generation of the inclination of the radiation flux intensity in the detecting element group **11**, and therefore, the radiation intensity distribution in the detecting element group **11** cannot be accurately acquired in some cases. With the shielding member **14** provided at the depletion **13**, the radiation detection device **1** can accurately acquire the intensity distribution even in the high-dose field, and can accurately estimate the radiation source location.

[0043] When the shielding member **14** is not provided at the depletion **13**, since the number of radiation rays entering the respective plurality of detecting elements **12** increases, the count number of photons can be increased in the whole detecting element group **11**. This allows the radiation detection device **1** to significantly improve the detection efficiency of radiation compared with the case where the shielding member **14** is provided at the depletion **13**. The improved detection efficiency leads to a reduction in measurement time. Since the reduction in measurement time allows reducing a dosage of radiopharmaceutical agent when the radiation detection device **1** is installed in medical equipment for radiation therapy, an effect of reducing radiation exposure of a patient can be provided. Accordingly, the radiation detection device **1** in which the shielding member **14** is not provided at the depletion **13** is effective when the radiation detection device **1** is installed in the medical equipment for radiation therapy or the like that requires the measurement time reduction.

[0044] In the detecting element group **11** illustrated in FIG. **3** and FIG. **4**, the virtual surface S includes a first virtual flat surface Sa, a second virtual flat surface Sb, and a third virtual flat surface Sc. The second virtual flat surface Sb is arranged to be opposed to the first virtual flat surface Sa. The third virtual flat surface Sc is arranged to be opposed to the second virtual flat surface Sb.

[0045] In the example of FIG. **3** and FIG. **4**, the first virtual flat surface Sa is an outer surface in the bottom side along the xy-plane. In the example of FIG. **3** and FIG. **4**, the second virtual flat surface Sb is a plane intersecting with the solid forming the outer shape of the detecting element group **11**, and is a plane passing between the detecting element **12***b* and a shielding member **14***a*. In the example of FIG. **3** and FIG. **4**, the third virtual flat surface Sc is a plane intersecting with the solid forming the outer shape of the detecting element group **11**, and is a plane passing between the detecting element **12***a* and the detecting element **12***b*.

[0046] In the example of FIG. **3** and FIG. **4**, the first virtual flat surface Sa, the second virtual flat surface Sb, and the third virtual flat surface Sc are defined to be stacked in a normal direction of the xy-plane based on a plane along the xy-plane. However, the first virtual flat surface Sa, the second virtual flat surface Sb, and the third virtual flat surface Sc may be defined to be not only stacked in the normal direction of the xy-plane, but also stacked in normal directions of an xz-plane and a yz-plane based on planes along the xz-plane and the yz-plane. Thus, the virtual surface S of the detecting element group **11** illustrated in FIG. **3** and FIG. **4** can be appropriately defined insofar as it is an outer surface of the solid forming the outer shape of the detecting element group **11** or a plane intersecting with the solid. The number of the virtual surfaces S can also be appropriately defined.

[0047] The detecting element group **11** illustrated in FIG. **3** and FIG. **4** includes a first detecting element group **11***a* in which the detecting element **12** and the depletion **13** or the shielding member **14** are arranged on the first virtual flat surface Sa, a second detecting element group **11***b* in which the detecting element **12** and the depletion **13** or the shielding member **14** are arranged on the second virtual flat surface Sb, and a third detecting element group **11***c* in which the detecting element **12** and the depletion **13** or the shielding member **14** are arranged on the third virtual flat surface Sc.

[0048] This allows the radiation detection device **1** to easily achieve the three-dimensional arrangement of the detecting element **12**, and to have the outer shape of the detecting element group **11** in a relatively simple polyhedron. Therefore, the radiation detection device **1** can avoid having the outer shape of the detecting element group **11** in a partially projecting shape. Accordingly, the radiation detection device **1** can be downsized with the radiation detector **10** that can be reduced in space.

[0049] Further, in the detecting element group **11** illustrated in FIG. **3** and FIG. **4**, the first virtual flat surface Sa, the second virtual flat surface Sb, and the third virtual flat surface Sc are arranged to be approximately mutually parallel. The first virtual flat surface Sa, the second virtual flat surface Sb, and the third virtual flat surface Sc are mutually arranged at regular intervals. The first virtual flat surface Sa, the second virtual flat surface Sb, and the third virtual flat surface Sc mutually have approximately the same square shape.

[0050] This allows the radiation detection device **1** to further easily achieve the three-dimensional arrangement of the detecting elements **12**, and to have the outer shape of the detecting element group **11** in a simple cube. Accordingly, the radiation detection device **1** can be further downsized with the radiation detector **10** that can be further reduced in space.

[0051] Furthermore, in the detecting element group **11** illustrated in FIG. **3** and FIG. **4**, at least one detecting element **12** in the first detecting element group **11***a*, at least one detecting element **12** in the second detecting element group **11***b*, and at least one detecting element **12** in the third detecting element group **11***c* are arranged at mutually different positions viewed in the normal direction of the first virtual flat surface Sa, the second virtual flat surface Sb, and the third virtual flat surface Sc.

[0052] This allows the radiation detection device **1** to reliably increase the difference of the detected values between the plurality of detecting elements **12** for the radiation having the direction perpendicular to the normal direction as the incident direction. Accordingly, the radiation detection device **1** can accurately estimate the source location of the radiation entering from the direction along the first virtual flat surface Sa, the second virtual flat surface Sb, and the third virtual flat surface Sc.

[0053] At least one detecting element **12** in the first detecting element group **11***a*, at least one detecting element **12** in the second detecting element group **11***b*, and at least one detecting element **12** in the third detecting element group **11***c* are preferably arranged at mutually different positions viewed in not only the normal direction of the xy-plane, but also the normal directions of the xz-plane and the normal direction of the yz-plane.

[0054] This allows the radiation detection device **1** to reliably increase the difference of the detected values between the plurality of detecting elements **12** for each of the radiations having the directions perpendicular to the respective normal directions as the incident directions. Accordingly, the radiation detection device **1** can further accurately estimate the source location of the radiation entering from all directions.

[0055] FIG. **5** is a diagram illustrating simulation results of estimation of the source location by the radiation detection device **1** including the detecting element group **11** illustrated in FIG. **3** and FIG. **4**.

[0056] First, simulation conditions will be described. Conditions regarding geometry of the detecting element group **11** are as follows. That is, the shape and the size of each of the detecting element **12**, the depletion **13**, and the shielding member **14** was a cube of 10 mm×10 mm×10 mm. As the detecting elements **12**, eight GAGG (Gadolinium Aluminum Gallium Garnet) scintillators were disposed. As the shielding members **14**, **18** lead blocks were disposed. One depletion **13** was provided. The arrangement of the detecting elements **12**, the depletion **13**, and the shielding members **14** was as illustrated in FIG. **4**.

[0057] Conditions regarding imaging of the source location are as follows. That is, the method of machine learning for generating the estimation model **52***a* was a neural network (one hidden layer). As training data, a gamma ray of 662 keV was irradiated on the detecting element group **11** for each of the incidence angles at every 10 degrees in both an azimuth angle φ and an elevation angle θ. For each of the incidence angles, the radiation irradiation for 10 minutes was performed 10 times. The count number of photons of the detecting element **12** was measured for the radiation entered in the detecting element group **11** from the respective incidence angles.

[0058] Conditions regarding test data are as follows. That is, the radiation source was ^{137}Cs (10 MBq). The number of photons was 102,708. The number of photons corresponds to the irradiation with a gamma ray from a source location apart from the detecting element group **11** by 3 m for 10 minutes. As the source location of the radiation, three patterns of P**1** to P**3** were prepared.

[0059] Next, the simulation result will be described. The horizontal axis of FIG. **5** indicates the azimuth angle φ of the incidence angle of the radiation, and the vertical axis of FIG. **5** indicates the elevation angle θ of the incidence angle of the radiation. In FIG. **5**, the darker the color mapped as the simulation result is, the higher the intensity of the detected radiation is, and it is indicated that the presence probability of the source location is high. In FIG. **5**, tips of arrows P**1** to P**3** indicate true source locations. As illustrated in FIG. **5**, it is seen that in each of the three patterns P**1** to P**3**, the true source location can be reproduced in the simulation result. Therefore, from the simulation result illustrated in FIG. **5**, it is seen that the radiation detection device **1** can accurately estimate the source location of the radiation.

[0060] FIG. **6** is a diagram illustrating a result of estimation of a source location by a conventional radiation detection device.

[0061] First, measurement conditions will be described. In this measurement, a Compton camera (manufacturer: Chiyoda Technol Corporation, product name: GAMMA Catcher) was used as a conventional radiation detection device. The radiation source was ^{137}Cs (10 MBq). The gamma ray was emitted from a source location apart from the Compton camera by 8 m for one hour.

[0062] Next, the estimation result of the source location will be described. The horizontal axis of FIG. **6** indicates the azimuth angle φ of the incidence angle of the radiation, and the vertical axis of FIG. **6** indicates the elevation angle θ of the incidence angle of the radiation. While the actual visual field of the conventional radiation detection device is in an angle range of ±70° from the center of the camera, it is converted into a visual field of 4π sr in FIG. **6** for facilitating the comparison with FIG. **5**. In FIG. **6**, the tip of an arrow P**4** indicates a true source location.

[0063] As illustrated in FIG. **6**, according to the conventional radiation detection device, it is seen that extra images appear in addition to the true source location. This is because the Compton camera images one Compton cone for one detection, and images a position at which the most Compton cones overlap as a position at which the presence probability of the source location is the highest after acquiring a large number of events. Therefore, according to the conventional radiation detection device, innumerable Compton cones appear, and they possibly become noise components in the estimation of the source location. Meanwhile, in the simulation result illustrated in FIG. **5**, the noise component as illustrated in FIG. **6** is reduced, and it is seen that the radiation detection device **1** of the embodiment can accurately estimate the source location of the radiation.

[0064] FIG. **7** is a perspective view illustrating an example of the radiation detector **10**. FIG. **8** is an exploded perspective view of the radiation detector **10** illustrated in FIG. **7**.

[0065] The radiation detector **10** illustrated in FIG. **7** and FIG. **8** includes a detecting element group **11**, a holder **21** that holds the detecting element group **11**, and a circuit board **22** that performs signal processing of the detecting element **12** to acquire the detected value.

[0066] The detecting element group **11** illustrated in FIG. **7** and FIG. **8** has a multi-layer structure similar to the detecting element group **11** illustrated in FIG. **3** and FIG. **4**, and includes a first detecting element group **11***a*, a second detecting element group **11***b*, and a third detecting element group **11***c*. The first detecting element group **11***a*, the second detecting element group **11***b*, and the third detecting element group **11***c* each have an outer shape formed in a square flat plate shape, and are stacked along a normal direction of the xy-plane.

[0067] The holder **21** and the circuit board **22** are provided for each of the first to the third detecting element groups **11***a* to **11***c*. The holder **21** holds the detecting element **12** and the shielding member **14**. At least the portion holding the detecting element **12** of the holder **21** is provided with a light transmitting portion **21***a*, such as a hole through which a light emitted from the detecting element **12** as a scintillator passes. The holder **21** is disposed to be opposed to the circuit board **22**, and secured by screws or the like. The circuit board **22** includes silicon photomultipliers (SiPMs) **23** that detect and amplify the light emission of the detecting elements **12**. The SiPM **23** is disposed at a position at least corresponding to the detecting element **12** on a mounting surface of the circuit board **22**. The circuit board **22** includes various kinds of electronic components necessary for acquiring the detected value of the detecting element **12** in addition to the SiPM **23**.

[0068] When the SiPMs **23** are disposed in all regions of the circuit board **22** opposed to the light transmitting portion **21***a*, the type, the arrangement, or the like of the detecting elements **12** appropriate for the measurement environment can be changed as necessary. This allows, for example, the improvement of detection efficiency of the radiation when the radiation detection device **1** is installed in the medical equipment for radiation therapy. Therefore, the radiation detection device **1** can easily change the design, for example, change the volume or the density of the detecting element **12**, or change the detecting element **12** to one having good radiation detection sensitivity.

[0069] The holder **21** and the circuit board **22** corresponding to the first detecting element group **11***a*, the holder **21** and the circuit board **22** corresponding to the second detecting element group **11***b*, and the holder **21** and the circuit board **22** corresponding to the third detecting element group **11***c* are disposed mutually at intervals via spacers **24**.

[0070] FIG. **9** is a diagram illustrating experimental results of an estimation of the source location by the radiation detector **10** illustrated in FIG. **7** and FIG. **8**.

[0071] First, experimental conditions will be described. Conditions regarding geometry of the detecting element group **11** are as follows. That is, the shape and the size of each of the detecting element **12**, the depletion **13**, and the shielding member **14** was a cube of 10 mm×10 mm×10 mm. As the detecting elements **12**, eight GAGG scintillators were disposed. As the shielding members **14**, 18 lead blocks were disposed. One depletion **13** was provided. The arrangement of the detecting elements **12**, the depletion **13**, and the shielding members **14** was as illustrated in FIG. **8**.

[0072] As a condition regarding imaging of the source location, a response function under the condition of irradiating the detecting element group **11** with a gamma ray for each of incidence angles at every 10 degrees in the azimuth angle φ (0 degrees to 350 degrees) was prepared.

[0073] Conditions regarding test data are as follows: the radiation source was ^{137}Cs (10 MBq). A gamma ray was emitted from a source location apart from the radiation detector **10** by 152.4 mm (6 inch) for three minutes. As the source location of the radiation, two patterns of P**5** and P**6** were prepared. The radiation source and the radiation detector **10** were placed on the same table, and only the azimuth angle φ of the incidence angle of the radiation was varied.

[0074] Next, the experimental result will be described. The center of the circle illustrated in FIG. **9** indicates the position of the radiation detector **10**. Numerical values in the circumferential direction of the circle illustrated in FIG. **9** indicate the azimuth angle φ. In FIG. **9**, the longer the length of the black bar chart mapped as the experimental result is, the higher the intensity of the detected radiation is, and it is indicated that the presence probability of the source location is high. In FIG. **9**, the azimuth angle φ of the true source location of P**5** is 0 degrees, and the azimuth angle φ of the true source location of P**6** is 225 degrees. As illustrated in FIG. **9**, it is seen that in both of the two patterns P**5** and P**6**, the true source location can be mostly reproduced in the experimental result. Therefore, from the experimental result illustrated in FIG. **9**, it is seen that the radiation detection device **1** can accurately estimate the source location of the radiation.

[0075] FIG. **10** is a diagram describing an example of another structure of the detecting element group **11**. FIG. **11** is a diagram describing an example of another structure of the detecting element group **11**. FIG. **12** is a diagram describing an example of another structure of the detecting element group **11**.

[0076] In the above-described embodiment, as illustrated in FIG. **3** and FIG. **4**, the detecting element group **11** is formed in a cubic shape having a multi-layer structure in which the first detecting element group **11***a* to the third detecting element group **11***c* are stacked. However, the shape and the structure of the detecting element group **11** may have any shape and structure insofar as the intensity distribution of the radiation in the detecting element group **11** is uniquely determined by the source location.

[0077] For example, as illustrated in FIG. **10**, the detecting element group **11** may be formed in a hemispherical shell shape having a hollow structure. The virtual surface S of the detecting element group **11** illustrated in FIG. **10** includes a virtual curved surface in a shape of hemisphere surface. Accordingly, the radiation detection device **1** eliminates the need for providing the multi-layer structure to the detecting element group **11** when 2π sr is enough for the required visual field. Therefore, the number of components can be reduced, thus allowing the cost reduction and the weight reduction.

[0078] For example, as illustrated in FIG. **11**, the detecting element group **11** may be formed in an L plate shape. The virtual surface S of the detecting element group **11** illustrated in FIG. **11** includes a virtual bending surface bent in an L shape. Accordingly, the radiation detection device **1** eliminates the need for providing the multi-layer structure to the detecting element group **11** when the incident direction of the radiation is limited to a specific direction. Therefore, the number of components can be reduced, thus allowing the cost reduction and the weight reduction.

[0079] In the above-described embodiment, the plurality of detecting elements **12** constituting the detecting element group **11** are three-dimensionally arranged. However, when the incident direction of the radiation is limited to a specific direction, the plurality of detecting elements **12** constituting the detecting element group **11** may be two-dimensionally arranged as illustrated in FIG. **12**. Therefore, in the radiation detection device **1**, the number of components can be further reduced, thus allowing the further cost reduction and the further weight reduction.

[0080] As described above, the radiation detection device **1** of this embodiment is a radiation detection device that includes the detecting element group **11** in which the plurality of detecting elements **12** that detect radiation are three-dimensionally arranged. The structure of the detecting element group **11** is a structure provided with the depletion **13** formed by removing the detecting element **12** at any position from the virtual detecting element group in which the detecting elements **12** are laid out on any virtual surface S. The depletion **13** is provided at a position at which a difference of detected values between one detecting element **12***a* and the other detecting element **12***b* arranged along any direction exhibits different values in a case where the radiation having the direction as the incident direction enters and a case where the radiation having an opposite direction of the direction as the incident direction enters.

[0081] This allows the radiation detection device **1** of the embodiment to provide mainly four advantages below, which are not provided by the conventional radiation detection device.

[0082] The first advantage is that the radiation detection device **1** has the visual field in all directions. Since the intensity distribution of the radiation generated in the detecting element group **11** includes the contribution of the radiation entering from all directions, by acquiring the intensity distribution, the radiation detection device **1** can perform the imaging in all directions by the single measurement.

[0083] The second advantage is that the radiation detection device **1** has wide application ranges of the energy and the dose rate of the radiation. In the case of a Compton camera, the energy of photon as the detection target is limited to an energy range having Compton scattering as a main interaction. In the case of a coded mask type camera, since the coded mask has a limitation in shielding ability, the imaging accuracy for the photon having high energy significantly decreases. Additionally, since the Compton camera requires coincidence with the signals of the multiple detecting elements, the signal processing circuit for acquiring the detected value is complicated, and the application to the high-dose field having the high detection rate is difficult.

In contrast, the radiation detection device **1** is applicable to various types of the radiation by selecting the respective types, the arrangement, or the like of the detecting element **12**, the depletion **13**, and the shielding member **14** appropriate for the photon energy as the target. Additionally, by appropriately selecting the respective sizes and numbers of the detecting elements **12**, the depletions **13**, and the shielding members **14**, the radiation detection device **1** is applicable to from the low-dose field, such as an outdoor environment, to the ultra-high dose field, such as an inside of a nuclear reactor.

[0084] The third advantage is that the device configuration is simple, and the size and weight can be reduced. In the case of a pinhole camera, to shield against entering of the radiation from a position other than the pinhole, the whole detector needs to be covered with a thick shield. This makes the total weight of the pinhole camera tens of kilograms or more. Meanwhile, the radiation detection device **1** does not need to include the shielding member **14** insofar as the depletion **13** as described above is provided. Even when the shielding member **14** is used, the radiation detection device **1** only needs to include the shielding member **14** that at least generates the inclination of the radiation flux intensity in the detecting element group **11** regarding the photon of the energy of radiation as the target. Therefore, in the radiation detection device **1**, even when the shielding member **14** is used, the weight of the radiation detector **10** can be suppressed to from several hundred grams to several kilograms or less. The weight of this degree allows the radiation detection device **1** to be easily mounted to a compact robot or a drone, thus greatly expanding the range of applications. Further, also in the application to an artificial satellite or the like where the weight of detector is considerably important, the radiation detection device **1** is extremely advantageous. Moreover, in the radiation detection device **1**, since several number of the detecting elements **12** are sufficient, the device configuration is simple, and the signal processing circuit for acquiring the detected value of the detecting element **12** only needs to be simple as well. The radiation detection device **1** can be manufactured at low price.

[0085] The fourth advantage is that the detecting element group **11** can employ any shape and structure. Usually, the gamma-ray imager has the visual field, the detection efficiency, and the spatial resolution that significantly vary depending on the shape and the structure of the detector, and therefore, the common shape and structure cannot be largely changed. In contrast, the radiation detection device **1** estimates the source location of the radiation from the intensity distribution of the radiation in the detecting element group **11**. Therefore, the detecting element group **11** may have any shape and structure insofar as the intensity distribution is uniquely determined by the source location. This advantage is effective when the installation site of the radiation detection device **1** is limited.

[0086] Thus, this embodiment can provide the novel radiation detection device **1** that is wide in visual field, wide in application range of radiation energy, and at the same time smaller and lighter in weight.

[0087] While the embodiment of the present invention is described above in detail, the present invention is not limited to the above-described embodiment, and various changes can be made without departing from the spirit of the present invention described in the claims. In the present invention, a configuration of one embodiment can be added to a configuration of another embodiment, a configuration of one embodiment can be replaced with a configuration of another embodiment, and a part of configurations of one embodiment can be deleted.

DESCRIPTION OF SYMBOLS

[0088] **1** Radiation detection device
[0089] **10** Radiation detector
[0090] **11** Detecting element group
[0091] **11***a* First detecting element group
[0092] **11***b* Second detecting element group
[0093] **11***c* Third detecting element group
[0094] **12** Detecting element
[0095] **12***a* One detecting element
[0096] **12***b* Other detecting element
[0097] **13** Depletion
[0098] **14** Shielding member
[0099] **50** Arithmetic processing unit
[0100] **51** Processing unit
[0101] **52** Estimation unit
[0102] **52***a* Estimation model
[0103] S Virtual surface
[0104] Sa First virtual flat surface
[0105] Sb Second virtual flat surface
[0106] Sc Third virtual flat surface

What is claimed is:

1. A radiation detection device comprising:

a detecting element group in which a plurality of detecting elements that detect radiation are three-dimensionally arranged,

wherein the detecting element group has a structure provided with a depletion formed by removing the detecting element at any position from a virtual detecting element group in which the detecting elements are laid out on any virtual surface, and

wherein the depletion is provided at a position at which a difference of detected values between one detecting element and another detecting element arranged along any direction exhibits different values in a case where the radiation having the direction as an incident direction enters and a case where the radiation having an opposite direction of the direction as an incident direction enters.

2. The radiation detection device according to claim **1**, wherein at least a part of the depletions is provided with a shielding member that shields against the radiation.

3. The radiation detection device according to claim **1**, wherein the virtual surface includes a first virtual flat surface and a second virtual flat surface arranged to be opposed to the first virtual flat surface, and wherein the detecting element group includes a first detecting element group in which the detecting element and the depletion are arranged on the first virtual flat surface, and a second detecting element group in which the detecting element and the depletion are arranged on the second virtual flat surface.

4. The radiation detection device according to claim **3**, wherein the first virtual flat surface and the second virtual flat surface are arranged to be approximately mutually parallel; and wherein the first virtual flat surface and the second virtual flat surface mutually have approximately a same square shape.

5. The radiation detection device according to claim **3**, wherein at least one of the detecting elements in the first detecting element group and at least one of the detecting elements in the second detecting element group are arranged at mutually different positions viewed in a normal direction of the first virtual flat surface and the second virtual flat surface.

6. The radiation detection device according to claim **1**, wherein the virtual surface includes a virtual curved surface in a shape of a hemisphere surface.

7. The radiation detection device according to claim **1**, further comprising an arithmetic processing unit, wherein the arithmetic processing unit includes a processing unit that acquires a spatial intensity distribution of the radiation in the detecting element group based on respective detected values of the plurality of detecting elements, and an estimation unit that estimates a source location of the radiation based on an acquisition result of the intensity distribution.

8. The radiation detection device according to claim **7**, wherein the estimation unit includes an estimation model that estimates the source location from the acquisition result of the intensity distribution, and wherein the estimation model is a model preliminarily generated through a machine learning based on training data in which the intensity distribution acquired for each incidence angle of the radiation to the detecting element group is associated with the source location at the acquisition of the intensity distribution.

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