(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
9 August 2012 (09.08.2012)

(10) International Publication Number
WO 2012/104798 A2

(51) International Patent Classification:
G01T 1/20 (2006.01)

(21) International Application Number:
PCT/IB2012/050468

(22) International Filing Date:
1 February 2012 (01.02.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/439,094 3 February 2011 (03.02.2011) US

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

WO 2012/104798 A2

(54) Title: RADIATION SENSITIVE IMAGING DETECTOR INCLUDING A RADIATION HARD WAVELENGTH SHIFTER

(57) Abstract: A radiation sensitive detector array (114) including a detector (116) with a scintillator (122, 202, 502, 504, 602, 606, 702, 704, 706) and a photo-sensor (120, 206, 508, 510, 612, 614, 708, 710, 712), including an optical photon sensitive region (206, 512, 514, 616, 618, 708, 710, 712) in optical communication with the scintillator array, wherein the detector also includes one or more wavelength shifters.

RADIATION SENSITIVE IMAGING DETECTOR INCLUDING A RADIATION HARD WAVELENGTH SHIFTER

FIELD OF THE INVENTION

The following generally relates to imaging and more particular to a radiation sensitive imaging detector including a radiation hard wavelength shifter, which may improve the detective quantum efficiency (DQE) of the detector. It is described with particular application to computed tomography (CT), including medical and/or non-medical applications such as baggage inspection, non-destructive testing, etc. However, the following is also applicable to non-CT imaging modalities such as nuclear medicine (NM) and/or other imaging modalities, especially to diagnostic digital and fluorescent x-radiology and to industrial radiology.

BACKGROUND OF THE INVENTION

A computer tomography (CT) scanner includes an x-ray tube that emits x-ray radiation that traverses an examination region and illuminates a single or dual-energy detector array disposed across the examination region from the x-ray tube. A single-energy detector array has included one or more one dimensional scintillator arrays optically coupled to corresponding one dimensional photo-sensor arrays. By way of example, a conventional single-energy integrating detector has included a gadolinium oxysulfide (GOS) scintillator array optically coupled to a silicon (Si) photodiode array. A dual-energy detector array has included one or more two dimensional scintillator arrays optically coupled to corresponding two dimensional photo-sensor arrays in which a top scintillator array includes a first material for absorbing lower energy “soft” x-ray photons and a bottom scintillator array having a second material for absorbing higher energy “hard” x-ray photons. By way of example, a conventional dual-energy detector has included a top zinc selenide (ZnSe) scintillator and a bottom GOS scintillator.

The x-ray radiation traversing the examination region illuminates the scintillator array, which absorbs the x-ray photons and, in response, emits optical photons indicative of the absorbed x-ray photons. The photodiode array detects the optical photons and generates an electrical (current or voltage) signal indicative of the detected optical photons. A reflective coating (e.g., a water-based acrylic paint containing anatase titanium dioxide (TiO_2) or an epoxy-based coating containing rutile TiO_2) over the scintillator reflects optical photons towards the photo sensor. The detected quantum efficiency (DQE) of the detector generally has been defined in the literature as the percentage of the total radiation illuminating the scintillator that is detected by the detector. Various factors affect the DQE. By way of example, spectral mismatch between the scintillator and the photo sensor, optical photons leaving the scintillator without being sensed by the photodiode, optical photons scattering within the scintillator, and/or optical photons being absorbed by optical absorption bands may affect the DQE of a detector.

SUMMARY OF THE INVENTION

Aspects of the present application address the above-referenced matters and others.

According to one aspect, a radiation sensitive detector array including a detector with a scintillator and a photo-sensor, including an optical photon sensitive region in optical communication with the scintillator array, wherein the detector also includes one or more wavelength shifters.

According to another aspect, a method includes detecting radiation with a radiation sensitive detector array of an imaging system, wherein the detector includes at least one detector with one or more wavelength shifters.

According to another aspect, an imaging system includes a radiation source that emits radiation that traverses an examination region and a detector array including at least one detector that detects radiation traversing the examination region and generates a signal indicative thereof. The detector includes a scintillator and a photo sensor with an optical photon sensitive region in optical communication with the scintillator array. The detector also includes one or more wavelength shifters. A reconstructor reconstructs the signal and generates volumetric image data indicative of the examination region.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 schematically illustrates an example imaging system with a detector including wavelength shifter.

FIGURE 2 schematically illustrates an example of the detector.

FIGURE 3 graphically shows an example quantum efficiency curve for CIGS as a function of wavelength.

FIGURE 4 graphically shows an example of emission spectra of the various materials as a function of wavelength.

FIGURE 5 schematically illustrates an example in which the detector is a dual energy detector with a reflector that includes a wavelength shifter.

FIGURE 6 schematically illustrates an example in which the detector is a dual energy detector with a composite scintillator that includes a wavelength shifter.

FIGURE 7 schematically illustrates an example in which the detector is a dual energy detector with a printed composite scintillator that includes a wavelength shifting dye.

FIGURE 8 illustrates an example method for imaging using a detector having a wavelength shifter.

DETAILED DESCRIPTION OF EMBODIMENTS

FIGURE 1 illustrates an imaging system 100 such as a computed tomography (CT) scanner. The imaging system 100 includes a stationary gantry 102 and a rotating gantry 104, which is rotatably supported by the stationary gantry 102. The rotating gantry 104 rotates around an examination region 106 about a longitudinal or z-axis 108.

A radiation source 110, such as an x-ray tube, is supported by and rotates with the rotating gantry 104, and emits poly-energetic radiation. A source collimator 112 collimates the emitted radiation to form a generally cone, fan, wedge, or otherwise shaped radiation beam that traverses the examination region 106 and an object or subject therein.

A radiation sensitive detector array 114 is affixed to the rotating gantry 104 and subtends an angular arc, across from the radiation source 110, opposite the examination region 106. The illustrated detector array 114 includes at least one detector 116, including a substrate 118 with one or more optical photon sensitive regions 120_1, 120_2, …, 120_N, respectively optically coupled to one or more scintillators 122_1, 122_2, …, 122_N. The detector array 114, in response to the scintillators detecting radiation, generates an output signal indicative of the detected radiation.

Examples of suitable detectors are described at least in application serial number 11/912,673, filed April 26, 2006, and entitled “Double Decker Detector for Spectral CT,” application serial number 12/067,942, filed September 14, 2006, and entitled “Computer Tomography Detector Using Thin Circuits,” and application entitled “Single and/or Multi-Energy Vertical Radiation Sensitive Detectors” (docket 015931), all of which are expressly incorporated herein in their entireties by reference.

As described in greater detail below, one or more wavelength shifters (e.g., radiation hard) are variously employed with the detector 116 and can improve the detective quantum efficiency (DQE) of the detector 116, relative to a configuration in which such wavelength shifters are omitted, by, for example, improving matching scintillator emission and photo sensor sensing wavelengths, improving reflecting optical photons towards the photo-sensor, decreasing optical photons scatter within the scintillator, and/or distancing the optical photon wavelength from absorption bands.

A reconstructor 124 reconstructs the signal using a conventional or spectral reconstruction algorithm, and generates volumetric image data indicative of the examination region 106. One or more conventional or spectral images can be generated from the volumetric image data.

A subject support 126, such as a couch, supports an object or subject in the examination region 106. The support 126 is movable along the x, y and z-axes in coordination with the rotation of the rotating gantry 104 to facilitate helical, axial, or other desired scanning trajectories.

A general purpose computing system serves as an operator console 128, which includes human readable output devices such as a display and/or printer and input devices such as a keyboard and/or mouse. Software resident on the console 128 allow the operator to control an operation of the system 100, for example, by allowing the operator to initiate scanning, etc.

As briefly discussed above, the detector 116 includes one or more wavelength shifters. The following provides some specific but non-limiting examples.

FIGURES 2, 3 and 4 schematically illustrate an embodiment in which a wavelength shifter is disposed between the scintillator and the photo-sensor, which may facilitate improving spectral matching of the scintillator and the photo-sensor.

Initially referring to FIGURE 2, the detector 116 includes a GOS scintillator 202 optically coupled to a wavelength shifter 204 that is optically coupled to a copper indium gallium diselenide (CIGS) photovoltaic semiconductor photo sensor 206. Other suitable photo sensors include, but are not limited to, silicon (Si), gallium arsenide (GaAs), indium phosphide (InP), and/or other photo sensors.

Turning to FIGURE 3, an example quantum efficiency curve 302 for CIGS as a function of wavelength is shown. A y-axis 304 represents quantum efficiency (e.g., as a percent) and an x-axis 306 represents wavelength (e.g., in nanometers). From FIGURE 3, in this example, CIGS has a quantum efficiency of about eighty seven percent (87%) at about five hundred and eighty nanometers (580 nm), but less than 70% at 500nm.

The GOS spectrum has a strong emission peak at about five hundred and ten nanometers (510 nm). Unfortunately, the QE of the CIGS at this wavelength is only about 71%. So the wavelength shifter 204 is used, to absorb optical photons in a range around 510 nm and to emit optical photons in a range around 580 nm where the CIGS photodiode has a relatively high quantum efficiency such as nearly ninety percent (90%). The large difference in quantum efficiency more than cancels out quantum efficiency losses for efficiently emitting wavelength shifters.

In a variation, the scintillator 202 includes an alkaline earth iodide doped with Eu^{2+} (e.g., Eu doped calcium iodide (CaI_2:Eu), Eu doped strontium iodide (SrI_2:Eu) or Eu doped barium iodide (BaI_2:Eu) or undoped SrI_2. SrI_2:Eu has a conversion efficiency that surpasses 100,000 photons/MeV, and its energy resolution can be extremely high (some 2%), approaching physical limits. Its melting point is low (538 °C), which renders it very suitable for single crystal growth, and its crystal structure is orthorhombic. CaI_2:Eu, undoped SrI_2 and BaI_2:Eu also have very high light yields.

Note that CaI_2:Eu, SrI_2:Eu, BaI_2:Eu, SrI_2, GOS, ZnSe, ZnSe, ceramic alkaline earth iodides doped with Eu^{2+}, other scintillators doped with Eu^{2+}, Ce^{3+} or Pr^{3+} or other activator ions, and/or other scintillators are discussed in application serial number 60/XXX,YYY, file December Z, 2010, and entitled “Single and/or Multi-Energy Vertical Radiation Sensitive Detectors,” which, as noted above, in incorporated herein by reference.

Turning to FIGURE 4, emission spectra of above materials as a function of wavelength is graphically shown. From FIGURE 4, the subject scintillators have strong emission in the ultraviolet (UV)/blue part of the electromagnetic spectrum. More specifically, CaI_2:Eu has an emission peak 402 around four hundred and sixty nanometers (460 nm), SrI_2:Eu has a peak 404 around four hundred and thirty nanometers (430 nm), BaI_2:Eu has a peak 406 around four hundred and ten nanometers (410 nm), $SrBr_2$:Eu has a peak 408 around four hundred nanometers (400 nm), and undoped SrI_2 has a peak 410 around five hundred and thirty nanometers (530 nm), in regions where some photo sensors such as CIGS have low sensitivity..

For this variation, the scintillator 206 includes one or more of the wavelength shifters shown in TABLE 1 and/or other wavelength shifter:

Material	Absorption maximum (nm)	Emission maximum (nm)	QE(%)
Perylene	420	430-460	94
Rhodamine 101	430	580	
Rhodamine 6G	488	550-800	95
Fluorescein	496	540 – 800	97
Rhodamine123	500	> 500	90
Rhodamine B	520	560	70
Sulforhodamine 101	590	> 590	
EJ-284	520-570	590-640	94
EJ-280	400-46-	480-530	86

TABLE 1: Wavelength Shifters.

Generally, from TABLE 1, Rhodamine 101 or 6G, or EJ-280, can be used to shift the spectrum of any of the Eu-doped alkaline earths, or of undoped SrI_2, to the 580 nm region, where the CIGS has almost 90% quantum efficiency. Pyridine 4 could also be used. Its absorbance is A=1 at 450nm. Perylene is especially wavelength hard.

Next, FIGURE 5 schematically illustrates an embodiment in which the detector 116 is a dual energy detector with a reflector that includes a wavelength shifter.

In this embodiment, a top or lower energy scintillator 502 includes a SrI_2:Eu scintillator crystal, and a bottom or higher energy scintillator 504 includes a GOS:Pr,Ce scintillator crystal. With GOS based scintillators, optionally, a wavelength shifter can be added to one or both of the scintillators 502 or 504, which may facilitate reducing optical photon scattering and/or optical photon absorption by Ce, which may be added to reduce afterglow. A suitable wavelength shifter would shift the emission wavelength of the scintillator away from the Ce^{3+} absorption band. With SrI2:Eu based scintillators, which may suffer from self absorbtion due to the low Stokes shift of this scintillator, such a wavelength shifter may distance the emission wavelength of the emitted light from the scintillator's own absorbtion band.

A reflective coating 506 covers a surface of at least one of the five sides of the scintillators 502 and 504, leaving uncoated at least the side to be optically coupled to a photo-sensor 516. The reflective coating 506 may include white reflective material with a wavelength shifter or a metallic material with a wavelength shifter.

In the former instance, the white reflective material may include a water-based acrylic paint containing anatase titanium dioxide (TiO_2,), epoxy-based coatings including rutile TiO_2, and/or other white reflective material, along with a wavelength shifter including perylene (with a minimal Stokes shift of only 10nm), rhodamine, pyridine, coumarin, and/or other material with suitable emission properties. In one non-limiting instance, the wavelength shifter is a dye that can readily be incorporated in the white reflective material of ceramic or crystalline scintillator arrays. EJ-280 or EJ-284 are available as thin wavelength-shifting plastic sheets with decay time less than 20 nano-seconds, and may be used inside the white coating.

In the latter instance, the metallic material may include silver (Ag), gold (Au), aluminum (Al), and/or other metallic material with suitable reflection properties. Generally, a metallic material can be applied as a thinner coating relative to the white reflective, and can be used in high definition CT (HDCT) detectors to reduce the gap between scintillator dixels. In the illustrated instance, the wavelength shifter is a dye that is incorporated into a white top coat, as a wavelength-shifting plastic sheet beneath the top white coat, and/or in an optical coupling adhesive, in addition to utilizing the metallic material.

In instances in which the Ag or Au are employed, the reflective coating 506 also includes one or more of perylene, rhodamine or fluorescein, EJ-284, or sulphur-Rhodamine, which has molar absorbtion > 40,000 at 510 nm, and emits at 90% quantum efficiency out to almost 800 nm. In the 500 nm region both Ag and Al have specular reflectance of 92%, whereas the specular reflectance of Au is much lower (about 50%), and Ag falls off even further below 500 nm. However, above 650nm Au is the highest (all are above 85%), and it is much less susceptible to atmospheric degradation. Thus an ideal wavelength shifter shifts the wavelength above 650nm, enabling the use of very thin gold plating, which is more stable than Al or Ag, and has higher reflectance.

A substrate 508 includes a photo sensor 510 having a top optical photon sensitive region 512 and a bottom optical photon sensitive region 514. The top and bottom scintillators 502 and 504 are optically coupled respectively to the top and bottom optical photon sensitive regions 512 and 514 via an optical epoxy coupling resin 516 that includes a wavelength shifter. In the illustrated embodiment, the wavelength shifter is pyridine-2.

A tungsten radiation shield 518 provides radiation shielding for the top and bottom optical photon sensitive regions 512 and 514 and the optical epoxy coupling resin 516 with the wavelength shifter.

FIGURE 6 schematically illustrates an embodiment in which the detector 116 is a dual energy detector with a composite scintillator that includes a wavelength shifter.

A top or lower energy scintillator 602 includes a scintillator powder and a wavelength shifter dispersed in clear resin. By way of non-limiting example, the scintillator 602 may include twenty percent (20%) SrI_2:Eu large grain powder and a wavelength shifter in clear resin. The height of the top scintillator 602 will depend on the halide density and concentration. In the illustrated embodiment, the 20% SrI_2 composite scintillator has a height (in the direction of incident radiation) of about six and a half (6.5) millimeters.

A reflective coating 604 such as a silver or white reflector is applied to a top surface of the top scintillator 602.

A bottom or higher energy scintillator 606 includes a scintillator powder and a wavelength shifter in clear resin. The height of the bottom scintillator 606 will depend on the scintillator density and concentration. By way of non-limiting example, the scintillator 606 may include fifty percent (50%) GOS:Pr,Ce large grain powder and a wavelength shifter in clear resin. In the illustrated embodiment, the bottom scintillator 606 has a height (the direction of the incident radiation) of about fifteen millimeters (15.0mm).

A reflective element 608 is disposed between the top and bottom scintillators 602 and 606, in the direction of the incident radiation. In the illustrated embodiment, the reflective element 608 includes an aluminum foil disposed between two white reflecting materials. The reflective element 608 may facilitate mitigating optical cross-talk between the top and bottom scintillators 602 and 606.

A substrate 612 includes a photo sensor 614 having a top optical photon sensitive region 616 and a bottom optical photon sensitive region 618. The top and bottom scintillators 602 and 606 respectively are optically coupled to the top and bottom optical photon sensitive regions 616 and 618 via an optical epoxy coupling resin 620 that includes a wavelength shifter. In the illustrated embodiment, the wavelength shifter is pyridine-2.

A back surface 622 of the substrate 612, which is opposite the top and bottom optical photon sensitive regions 616 and 618, includes a white reflective coating 624 with a reflective layer such as white reflective paint or a bright metallic layer.

A tungsten radiation shield 626 provides radiation shielding for the top and bottom optical photon sensitive regions 616 and 618 and for the optical epoxy coupling resin 620 with the wavelength shifter.

The wavelength shifter in the top and bottom scintillators 602 and 606 or the optical epoxy coupling resin 620 and/or in a white coating, may facilitate reducing optical photon scatter in the top and bottom scintillators 602 and 606. Generally, composite scintillators suffer from scattering on a greatly enhanced scale, and scattering increases with photon energy and is thus reduced at longer wavelengths.

FIGURE 7 schematically illustrates a sub-section of the detector 116, which is a dual energy detector with a printed composite scintillator that includes a wavelength shifting dye.

In illustrated embodiment, a top layer 702 includes a composite resin including eighty percent (80%) large grain SiI_2:Eu power to an equivalent thickness of six hundred and eighty (680) microns in epoxy or mercaptan resin with a wavelength shifter. In the illustrated embodiment, the composite resin includes one tenth of a percent (0.1%) pyridine-2 wavelength shifter. Other wavelength shifters are also contemplated herein.

In illustrated embodiment, the first bottom layer 704 includes a one thousand five hundred (1500) micron composite layer with epoxy or mercaptan resin having seventy-five (75%) GOS powder of mean grain size of greater than twenty (20) microns, free of fines, and with a wavelength shifter. The second layer 706 may be 3mm (three thousand microns) thick. In the illustrated embodiment, the wavelength shifter is pyridine-2. Other wavelength shifters are also contemplated herein. In other embodiments, the bottom layer may include more than two layers.

Printed photodiode arrays 708, 710, and 712 are respectively disposed between the top layer 702 and the first bottom layer 704, the first bottom layer 704 and the second bottom layer 706, and under the second bottom layer 706. The intermediate photodiode array 710 is mounted upon a transparent TCO substrate, so that its elements are sensitive to photons both from the front and from the back sides. For this reason the lower composite layer 706 may have twice the thickness of the upper layer 704. In the illustrated embodiment, the photodiode arrays 708-712 include copper indium gallium diselenide (CGIS). Other photodiodes are also contemplated herein.

Not shown in FIGURE 7 is the impervious coating, including, for example, silicon oxides in polyethylene film, which facilitates preventing attack by moisture or atmospheric oxygen upon the SrI_2 top layer.

A wavelength-shifting plastic sheet, such as EJ-284, may be placed beneath this layer, juxtaposed to the composite resin, to replace the wavelength shifter incorporated in the top layer.

FIGURE 8 illustrates an imaging method.

At 802, x-ray radiation is absorbed by the detector including one or more wavelength shifters.

At 804, the x-ray radiation is converted by a scintillator of the detector to optical photons indicative of the detected radiation. As described herein, the scintillator may include at least one wavelength shifter. Additionally or alternatively, a reflector disposed over the scintillator may include at least one wavelength shifter.

At 806, the optical photons are detected via a photo sensor of the detector. As described herein, the scintillator is optically coupled to the photo sensor, and the optical coupling may also include at least one wavelength shifter.

At 808, the optical photons are converted by the photo sensor to an electrical signal indicative of the detected radiation.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS

What is claimed is:

1. A radiation sensitive detector array (114), comprising:
a detector (116), including:
a scintillator (122, 202, 502, 504, 602, 606, 702, 704, 706); and
a photo-sensor (120, 206, 508, 510, 612, 614, 708, 710, 712), including an optical photon sensitive region (206, 512, 514, 616, 618, 708, 710, 712) in optical communication with the scintillator array, wherein the detector also includes one or more wavelength shifters.

2. The radiation sensitive detector array of claim 1, wherein the wavelength shifter includes at least one of pyridine, perylene, rhodamine 101, rhodamine 6G, fluorescein, rhodamine123, rhodamine B, sulforhodamine 101, EJ-284 or EJ-280.

3. The radiation sensitive detector array of any of claims 1 to 2, wherein the scintillator includes at least one of CaI_2:Eu, SrI_2:Eu, BaI_2:Eu, or SrI_2.

4. The radiation sensitive detector array of any of claims 1 to 3, the detector, further comprising;
a reflective coating (604) covering the scintillator, wherein the reflective coating includes the wavelength shifter.

5. The radiation sensitive detector array of claim 4, wherein the wavelength shifter improves an optical photon collection efficiency of the detector.

6. The radiation sensitive detector array of any of claims 1 to 5, wherein the scintillator is a composite scintillator and the wavelength shifter is incorporated into the composite scintillator.

7. The radiation sensitive detector array of claim 6, wherein the wavelength shifter increases a wavelength of optical photons, thereby reducing optical photon scatter in the scintillator.

8. The radiation sensitive detector array of claim 6, wherein the wavelength shifter shifts a wavelength of optical photons away from an optical photon absorption band of the scintillator.

9. The radiation sensitive detector array of any of claims 1 to 6, further comprising:
an optical coupling (204) between the photo sensor and the sensitive region, wherein the optical coupling includes the wavelength shifter.

10. The radiation sensitive detector array of any of claims 1 to 9, wherein the detector is a single-energy detector.

11. The radiation sensitive detector array of any of claims 1 to 9, wherein the detector is a multi-energy detector, having at least two scintillator respectively optically coupled to two photo-sensors.

12. A method, comprising:
detecting radiation with a radiation sensitive detector array of an imaging system, wherein the detector includes at least one detector with one or more wavelength shifters.

13. The method of claim 12, wherein the detector includes a scintillator that includes at least one wavelength shifter.

14. The method of claim 12, wherein the detector includes a scintillator with a reflective coating that includes at least one wavelength shifter.

15. The method of claim 12, wherein the detector includes a scintillator optically coupled to a photo sensor via an optical coupling that includes at least one wavelength shifter.

16 An imaging system (100), comprising:

a radiation source (110) that emits radiation that traverses an examination region;

a detector array, including at least one detector that detects radiation traversing the examination region and generates a signal indicative thereof, the detector, comprising:

a scintillator; and

a photo sensor, including an optical photon sensitive region in optical communication with the scintillator array, wherein the detector also includes one or more wavelength shifter; and

a reconstructor (124) that reconstructs the signal and generates volumetric image data indicative of the examination region.

17. The imaging system of claim 16, wherein the scintillator includes SrI_2:Eu and the photo-sensor includes copper indium gallium diselenide.

18. The imaging system of claim 16, wherein scintillator is optically coupled to the photo sensor via an optical coupling, wherein the scintillator includes SrI_2:Eu and the wavelength shifter includes Pyridine, and wherein the optical coupling includes the wavelength shifter.

19. The imaging system of claim 16, further comprising:

an optical reflector coated on the scintillator, wherein scintillator includes SrI_2:Eu, wherein the optical reflector includes the wavelength shifter.

20. The imaging system of claim 19, wherein the optical reflector includes a white reflector and the wavelength shifter includes Pyridine.

21. The imaging system of claim 16, further comprising:

an optical reflector coated on the scintillator, wherein the scintillator includes GOS, wherein the optical reflector includes the wavelength shifters.

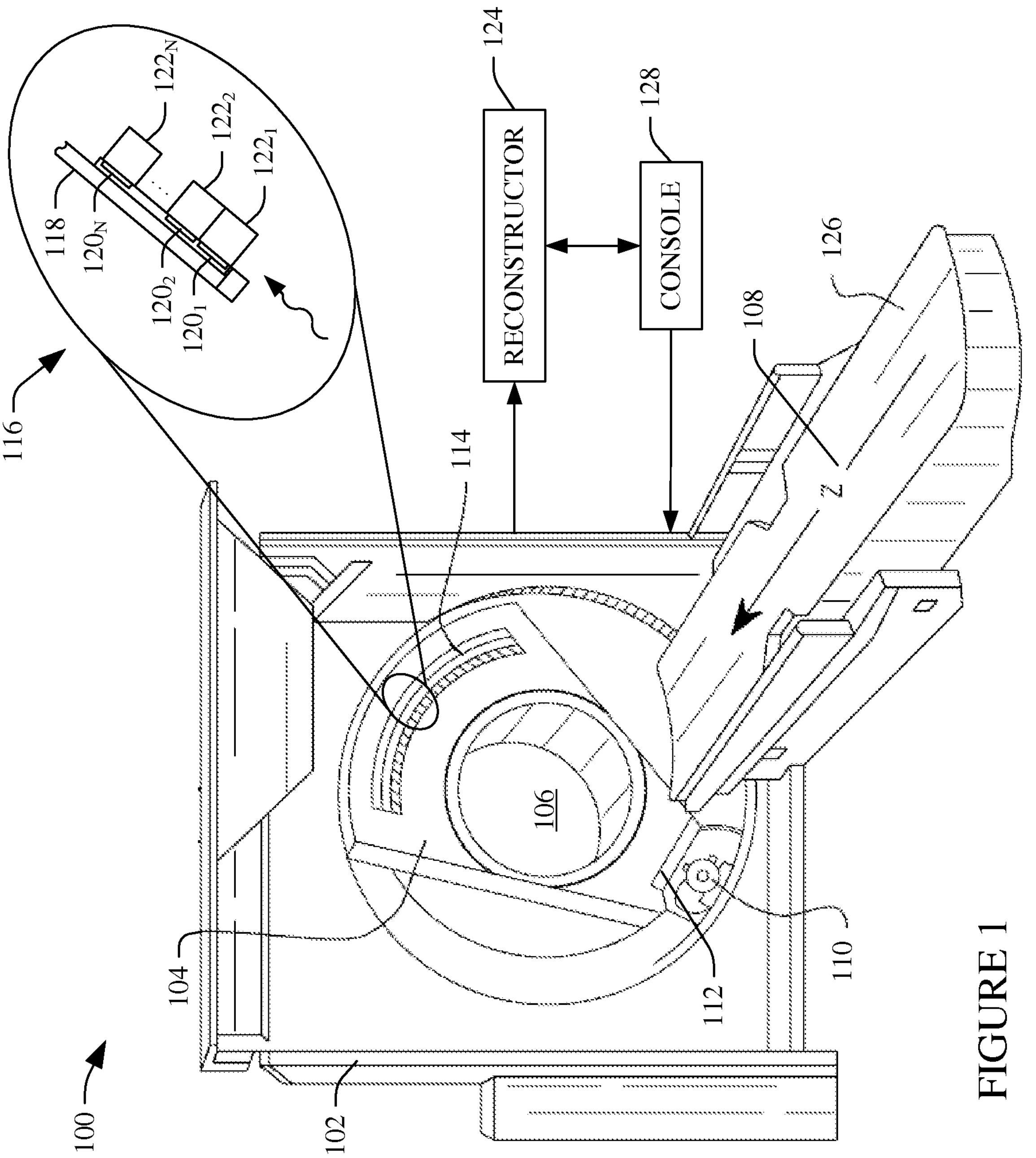
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FIGURE 1

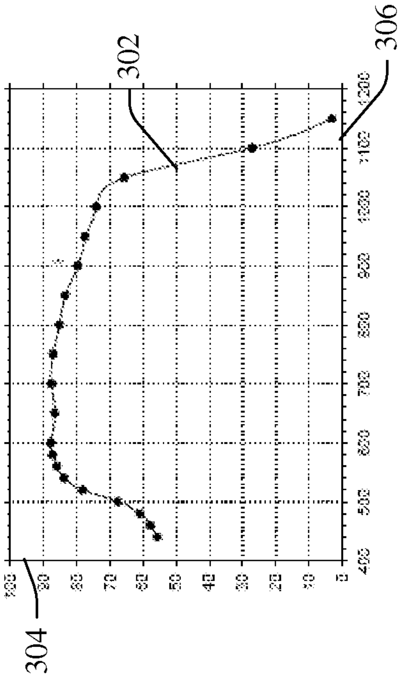

FIGURE 3

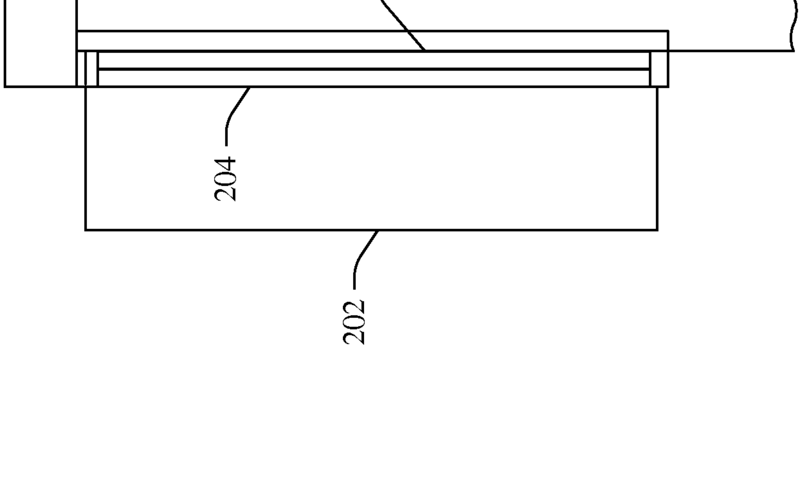

FIGURE 2

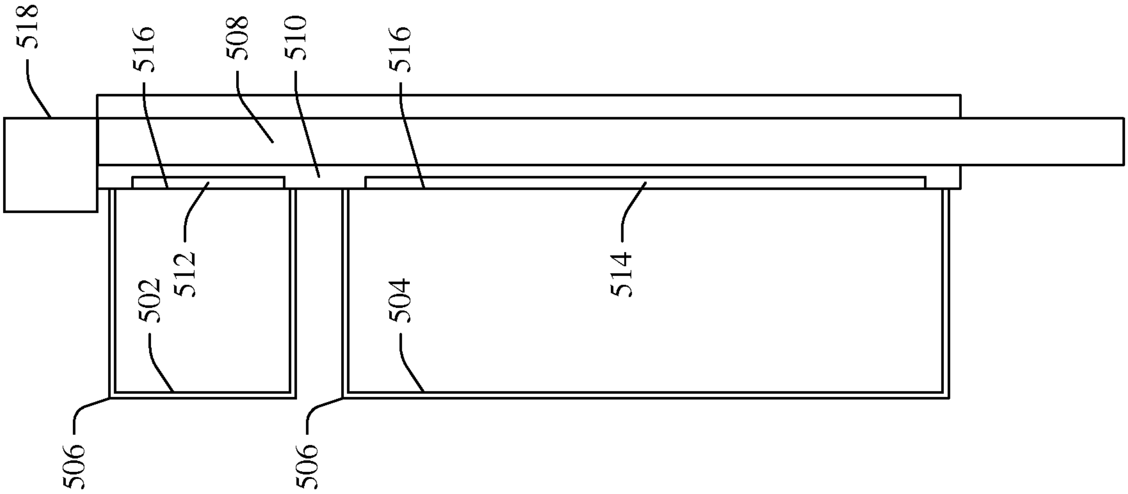

FIGURE 5

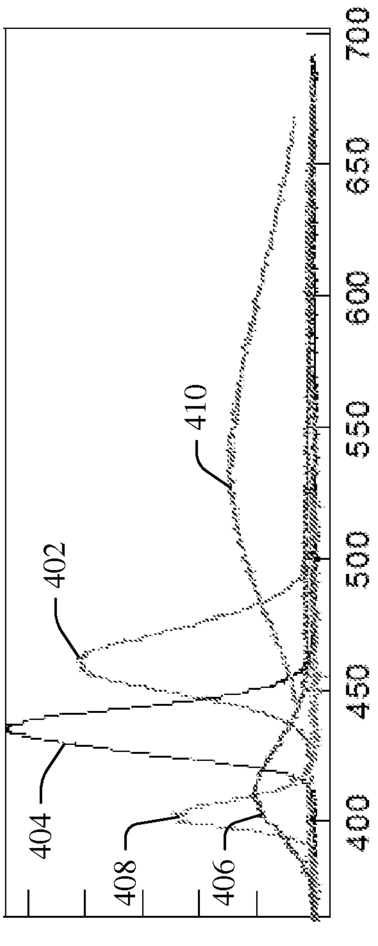

FIGURE 4

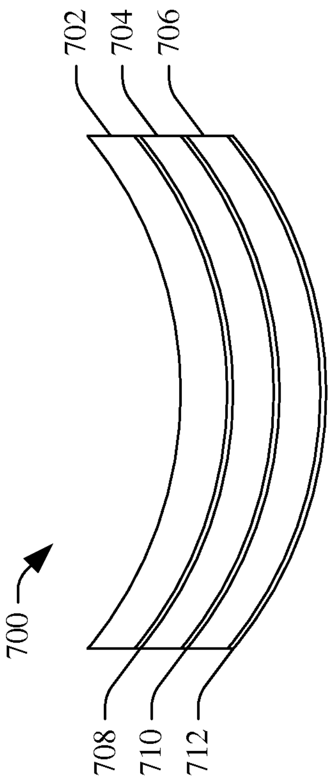

FIGURE 7

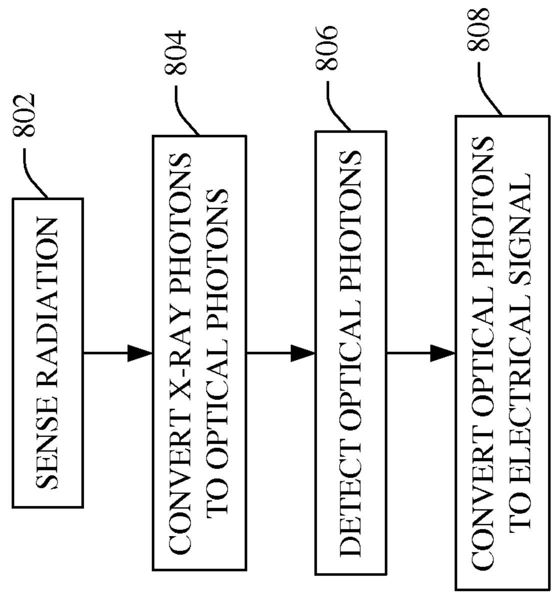

FIGURE 8

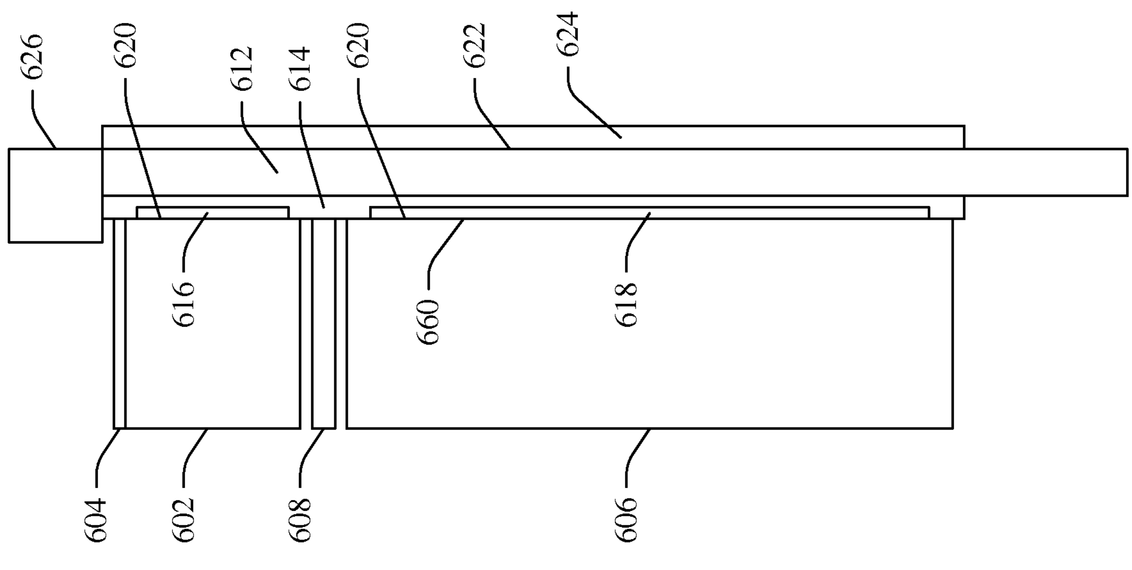

FIGURE 6