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(71) Applicant *(for all designated States except US)*: **PHOTODETECTION SYSTEMS, INC.** [US/US]; 16 Craig Road, Acton, MA 01720-5405 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **ROMANOV, Leonid** [US/US]; 188 Swanson Road, Boxboro, MA 01719 (US). **JOHNSON, Olof** [US/US]; 61 Young Road, Ashburnham, MA 01430 (US). **DOMIGAN, Paul** [US/US]; 120 Chestnut Street, Andover, MA 01810 (US).

(74) Agent: **LICHAUCO, Faustino, A.**; Fish & Richardson P.C., 1425 K Street, N.W., 11th Floor, Washington, DC 20005-3500 (US).

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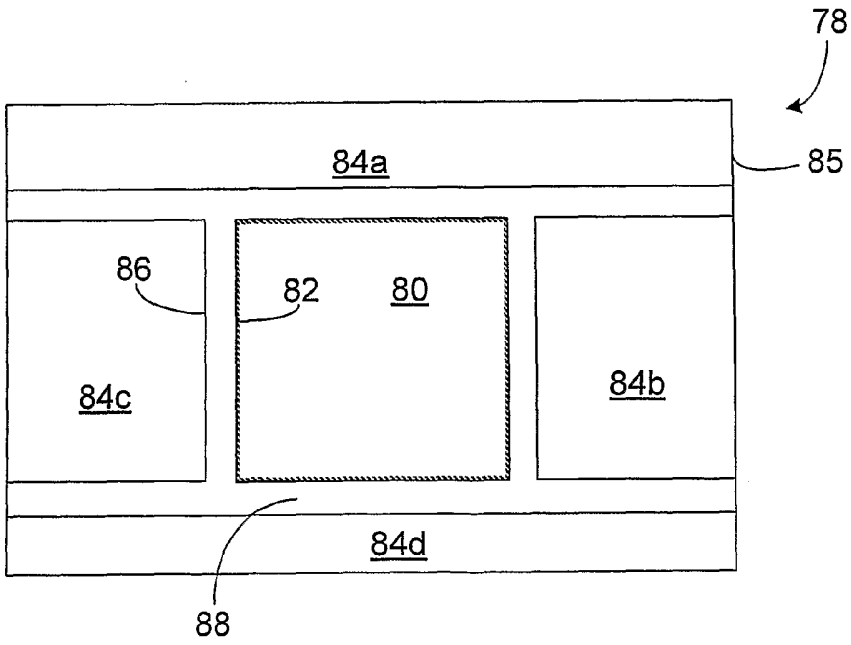
(54) Title: PET SCANNER WITH STRUCTURED OPTICAL ELEMENT



(57) Abstract: A PET scanner includes a scintillator block and a plurality of photodetectors, each of which has a field of view that includes a portion of the scintillator block. An optical element is disposed between the scintillator block and the plurality of photodetectors. The optical element has afirst layer and a second layer. The first layer has a central region and a peripheral region separated by a first gap. The second layer has at least a first region and a second region separated by a second gap.

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PET SCANNER WITH STRUCTURED OPTICAL ELEMENT

FIELD OF INVENTION

This invention relates to positron emission tomography ("PET") systems, and in particular, to enhancing spatial resolution of a PET system.

BACKGROUND

In positron emission tomography ("PET"), a radioactive material is placed in the patient. In the process of radioactive decay, this material emits positrons. These positrons travel through the patient until they encounter electrons. When a positron and an electron meet, they annihilate each other. This results in emission of two gamma ray photons traveling in opposite directions. By detecting these gamma ray photons, one can infer the distribution of the radioactive material within the patient.

Certain materials, referred to as scintillating crystals, emit an isotropic spray of scintillation photons centered at a point at which a gamma ray interacts with the material. Some of these scintillation photons are emitted in a direction that takes them to a photodetector. Other scintillation photons, which are emitted in a direction away from any photodetector, nevertheless manage to reach a photodetector after being redirected by structures within the scintillating crystal. Yet other scintillation photons are absorbed and therefore never reach the photodetector at all.

To detect gamma ray photons, the patient is positioned within a ring of scintillating crystals. Photodetectors observing the crystals can then detect the scintillation photons and provide, to a processor, information on how many coincident gamma ray photon pairs were received in a particular interval and at what location those gamma ray photon pairs originated. The processor then processes such data arriving from all photodetectors to form an image showing the spatial distribution of radioactive material within the patient.

Each photodetector provides a signal whose intensity indicates the number of scintillation photons reaching that photodetector. The resulting signal, however, does not provide precise information on where the gamma ray photon interacted with the scintillating crystal. This imprecision can limit the spatial resolution of the resulting image.

One approach to enhancing spatial resolution is to allow scintillation photons to reach more than one detector. By observing the relative numbers of scintillation photons received by each detector, it is possible to determine the location at which the gamma ray photon interacted with the scintillation crystal.

The success of this approach depends in part on controlling the distribution of scintillation photons that reach the detectors. This spatial distribution of scintillation photons can be controlled by a optical element placed between the scintillating crystal and the detectors.

SUMMARY

In one aspect according to the invention, a PET scanner includes a scintillator block and a plurality of photodetectors. A optical element is disposed between the scintillator block and the plurality of photodetectors. The optical element includes a first layer having a central region with an outer wall and a peripheral region with an inner wall separated from the outer wall by a first gap. The optical element also includes a second layer in optical communication with the first layer and having at least a first region and a second region. The first region has a first interior wall and the second region has a second interior wall opposite the first interior wall and separated therefrom by a second gap.

Embodiments of this aspect of the invention may include one or more of the following features.

The first layer has a perimeter wall, and the peripheral region is adjacent to at least a portion of the perimeter wall.

The peripheral region is adjacent to the entire perimeter wall.

The first layer has one or more additional peripheral regions, the one or more additional peripheral regions being adjacent to a portion of the perimeter wall that is not adjacent to the peripheral region.

An additional peripheral region is separated from the peripheral region by a gap.

The gap extends to the perimeter wall.

The inner wall and the outer wall have different optical characteristics.

An inner surface of the inner wall of the peripheral region has a greater reflection coefficient than an inner surface of the outer wall of the central region.

The inner surface of the inner wall is polished.

The inner surface of the outer wall is roughened.

The optical element has a third layer facing the scintillator block.

The first gap has an optical property that is different from a corresponding optical property of the central region and the peripheral region.

The first gap is an air gap.

The first interior wall and the second interior wall are specularly reflecting walls.

The second gap defines a grid of regions.

Each region in the grid of regions is positioned to correspond to a photodetector from the plurality of photodetectors.

The second gap is a cruciform gap.

According to another aspect of the invention, an optical element for directing light from a scintillator block to a plurality of photodetectors includes a first layer in optical communication with the scintillator block. The first layer has a central region having an outer wall and a peripheral region having an inner wall, the inner and outer wall being separated by a first gap. The optical element also has a second layer in optical communication with the plurality of photodetectors, and with the first layer. The second layer includes at least a first region and a second region. The first region has a first interior wall and the second region has a second interior wall opposite the first interior wall. The first and second interior walls are separated by a second gap.

Embodiments of this aspect of the invention may include one or more of the following features.

The inner wall and the outer wall are configured such that a photon incident on the inner wall from the peripheral region encounters a first reflection coefficient that is greater than a second reflection coefficient encountered by a photon incident on the outer wall from the central region.

An inner surface of the inner wall of the peripheral region has a greater reflection coefficient than an inner surface of the outer wall of the central region.

The inner surface of the inner wall is polished.

The inner surface of the outer wall is roughened.

The optical element further includes a third layer facing the scintillator block.

The first gap is an air gap.

The first interior wall and the second interior wall are specularly reflecting walls.

The second gap defines a grid of regions.

The second gap extends across the second layer.

The second gap extends part way across the second layer.

The cruciform gap has intersecting first and second arms, at least one of which extends across the second layer.

The cruciform gap has intersecting first and second arms that both extend part way across the second layer.

A mask is disposed to prevent scintillation photons emerging from selected portions of the optical element from reaching the photodetectors.

Each region in the grid of regions is positioned to correspond to a photodetector from the plurality of photodetectors.

The second gap is a cruciform gap.

According to another aspect of the invention, an optical element directs light from a scintillator block to a plurality of photodetectors. The optical element includes a first layer in optical communication with the scintillator block. The first layer has a central region having an outer wall and a peripheral region having an inner wall, the inner and outer walls being separated by a first gap. The optical element also has a second layer in optical communication with the plurality of photodetectors and with the first layer . The second layer includes at least a first region and a second region. The first region has a first interior wall and the second region has a second interior wall opposite the first interior wall. The first and second interior walls are separated by a second gap.

According to yet another aspect of the invention, a PET scanner includes a scintillator block for generating a spatial light distribution of scintillation photons in response to illumination by a gamma ray photon, means for an outer and inner the spatial light distribution of scintillation photons to generate a modified spatial light distribution, and a plurality of photodetectors for receiving the modified spatial light from the outer and inner means.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows a ring of modules;

FIGS. 2A and 2B show a detector block;

FIG. 3 shows the detector block of FIGS. 2A and 2B taken along the line 3-3;

FIG. 4 shows master/slave relationships between a subset of the modules shown in FIG. 1;

FIG. 5 shows connections between a master and its two slaves;

FIG. 6 is a flow-chart of a process carried out by a slave;

FIG. 7 is a flow-chart of a process carried out by a master;

FIG. 8A-C show exemplary response curves for detector blocks;

FIG. 9 is a cross-section of a structured optical element;

FIGS. 10, 11, and 12 are plan views of exemplary structured inner layers of the optical element of FIG. 9 taken along the line 10-10;

FIGS. 13, 14, and 15 are plan views of exemplary structured outer layers of the optical element of FIG. 9 taken along the line 11-11; and

FIG. 16 is a mask disposed on the optical element.

DETAILED DESCRIPTION

Referring to FIG. 1, a PET scanner **10** includes a ring **12** of detector modules **16A-K** surrounding a bed **14** on which a patient is to lie. Each detector module **16A-K** (hereinafter referred to as a "module") includes one or more rows of detector blocks **17**. A detector block **17**, shown in FIG. 2A, includes, for example, four photomultiplier tubes **19A-D** arranged in a 2x2 array in optical communication with a scintillator block **21**. The scintillator block **21** is typically made of CsI(Na) (sodium doped cesium iodide). Photomultiplier tubes **19A-B** are visible in FIG. 2A and photomultiplier tubes **19A-C** are

visible in FIG. 2B. The remaining photomultiplier tube **19D**, which lies diagonally across the array from photomultiplier tube **19A** is not visible.

The scintillator block **21** is divided into individual pillars **23** made of a scintillating crystal. The pillars **23** are arranged in an array, for example a 10x16 array, a portion of which is shown in FIG. 3. The array has a rectangular cross-section with a length of 3.22 inches (82 millimeters) and a width of 2.69 inches (68 millimeters).

Each pillar **23** in the array is a rectangular prism having a transverse cross-section with a long side **25** and a short side **27**. The axis parallel to the long side **25** will be referred to herein as the "major" axis of the scintillator block **21**, and the axis parallel to the short side **27** of the will be referred to herein as the "minor" axis of the scintillator block **21**.

To image a portion of a patient with a PET scanner **10**, one introduces a radioactive material into the patient. As the radioactive material decays, it emits positrons. A positron, after traveling a short distance through the patient, eventually encounters an electron. The resulting annihilation of the positron and the electron generates two gamma ray photons traveling in opposite directions. To the extent that neither of these gamma ray photons is deflected or absorbed within the patient, they emerge from the patient and strike two opposed pillars **23**, thereby generating a flash of light indicative of an event. By determining from which pillars **23** the light indicative of an event originated, one can estimate where in the patient the annihilation event occurred.

In particular, referring again to FIG. 1, when one of these gamma ray photons strikes a pillar in a first detector module **16A**, the other gamma ray photon strikes a pillar in a second detector module **16E, F, G,** or **H** opposed to the first detector module. This results in two events: one at the first detector module **16A** and the other at the opposed second detector module **16E, F, G,** or **H**. Each of these events indicates the detection of a gamma ray photon. If these two events are detected at the first detector module **16A** and the second detector module **16E, F, G,** or **H** at the same time, it is likely that they indicate an annihilation occurring on a line connecting first detector module **16A** and the second detector module **16E, F, G,** or **H.** If these two events are detected at the first

detector module **16A** and the second detector module **16E, F, G,** or **H** at almost the same time, it is likely that they indicate an annihilation occurring on a line connecting first detector module **16A** and the second detector module **16E, F, G,** or **H.**

It is apparent that what is of interest in a PET scanner **10** are pairs of events detected by opposed detector modules **16A, 16E-F** at, or almost at, the same time. A pair of events having these properties is referred to as a "coincidence." In the course of a PET scan, each detector module **16A-K** detects a large number of events. However, only a limited number of these events represent coincidences.

Associated with each detector module **16A-K** is a module processor **18A-K** that responds to events detected by its associated detector module **16A-K.** A module processor **18A-K** includes a processing element and a memory element in data communication with each other. The processing element includes a computational element containing combinatorial logic elements for performing various logical operations, an instruction register, associated data registers, and a clock. During each clock interval, the processor fetches an instruction from the memory element and loads it into the instruction register. Data upon which the instruction is to operate is likewise loaded into the associated data registers. At subsequent clock intervals, the processing element executes that instruction. A sequence of such instructions is referred to herein as a "process."

Each module processor **18A-K** executes a master process and a slave process concurrently. Each module processor **18A-K** is simultaneously a master of two module processors and a slave to two other module processors. As used herein, "master" shall mean a module processor **18A-K** acting as a master module processor and "slave" shall mean a module processor **18A-K** acting as a slave module processor. The terms "master module" and "slave module" shall be used to refer to the detector modules **16A-K** associated with the master and slave respectively.

The two slaves of each master are selected on the basis of the relative locations of their associated detector modules **16A-K** on the ring **12.** In particular, the slaves of each master are selected to maximize the likelihood that an event detected at the master

detector module and an event detected at any one of the slave detector modules form a coincidence pair.

For the configuration of eleven detector modules shown in FIG. 1, the master/slave relationship between module processors **18A-K** is as follows:

MASTER	SLAVE_1	SLAVE_2
18A	18E	18F
18B	18F	18G
18C	18G	18H
18D	18H	18I
18E	18I	18J
18F	18J	18K
18G	18K	18A
18H	18A	18B
18I	18B	18C
18J	18C	18D
18K	18D	18E

and the slave/master relationship between module processors **18A-K** is as follows:

SLAVE	MASTER_1	MASTER_2
18A	18G	18H
18B	18H	18I
18C	18I	18J
18D	18J	18K
18E	18K	18A
18F	18A	18B
18G	18B	18C
18H	18C	18D
18I	18D	18E

18J	18E	18F
18K	18F	18G

FIG. 4 shows the ring **12** of FIG. 1 with lines added to show the master/slave relationships of two of the eleven module processors. The lines connecting detector modules **16A** to **16E** and detector modules **16A** to **16F** indicate that module processors **18E** and **18F** are slaves of module processor **18A**. Module processor **18F** has its own two slaves, as indicated by the lines connecting detector module **16F** to detector modules **16J** and **16K**. The eighteen lines representing the remaining master/slave relationships are omitted for clarity.

As shown in FIG. 5, a master **18A** is connected to its first slave **18E** by first and second data links **20A, 22A**. Similarly, the master **18A** is connected to its second slave **18F** by additional first and second data links **20B, 22B.** The first and second data links **20A-B, 22A-B** are used to transmit trigger pulses between the master **18A** and the corresponding slave **18E-F**. Hence, the first and second data links **20A-B, 22A-B** are typically a single wire.

When a slave **18E** receives, from its associated detector module **16E,** a signal indicative of an event (hereinafter referred to as a "slave event"), it transmits a pulse to the master **18A** on the first data link **20A**. When the master **18A** considers a slave event detected by the slave **18E** to be a constituent event of a coincidence, it sends a pulse back to that slave **18E** on the second data link **22A**.

A third data link **24A-B**, which is typically an LVDS ("low-voltage differential standard") channel connects the master **18A** and each of its slaves **18E-F**. The slaves **18E-F** use this third data link **24A-B** to transmit to the master **18A** additional information about slave events. Such additional information can include, for example, the energy of the incident gamma ray photon that triggered that slave event, and the waveform of the voltage signal generated by the photo multiplier tube.

FIG. 6 shows the procedure carried out by a slave. Upon receiving, from its associated module processor, a signal indicative of a slave event (step **26**), a slave reports the detection of that slave event to both of its respective masters (steps **28A-B**). It does so by transmitting a pulse on each of two first data links that connect it to those masters. The slave then waits for a response from its masters on either of the two second data links connecting it to each of those two masters (steps **30A-B**).

In response to a request pulse received on the second data link from a master, the slave prepares a data packet containing additional information about the slave event (steps **32A-B**). This data packet is then transmitted on the third data link to whichever of its masters requested that additional information (steps **34A-B**). After sending the data packet, the slave waits for the next event (step **36**). If neither master sends a request pulse within a pre-defined time interval, the slave discards the slave event (step **38**) and waits for the next slave event (step **36**).

FIG. 7 shows the procedure carried out by a master. Upon receiving, from its associated detector module, a signal indicative of a slave event (step **40**), the master compares the occurrence time of that slave event with occurrence times of events (hereinafter referred to as "master events") received by its own associated detector module (step **42**). If the occurrence times of a master event and a slave event differ by no more than a selected tolerance, the master considers that master event and that slave event to be a coincidence (step **44**). Otherwise, the master ignores the slave event and waits for the next slave event (step **46**).

Upon recognizing a coincidence between a master event and a slave event, the master transmits a request pulse to whichever slave detected that slave event (step **48**). As described in connection with FIG. 6, this pulse is interpreted by the slave as a request for additional information about that slave event. The master then waits for the data packet containing additional information about the slave event.

Upon receiving the data packet (step **50**), the master creates a coincidence record that includes information about the master event and the slave event that together make up the coincidence. This coincidence record is stored on a mass storage medium, such as

a magnetic disk or a magnetic tape, (step **52**) for later processing by an image-reconstruction process executing known tomography algorithms.

As described herein, each slave has two masters and each master has two slaves. However, there is no requirement that a slave have a particular number of masters or that a master have a particular number of slaves. Nor is there a requirement that each master have the same number of slaves or that each slave have the same number of masters.

The illustrated PET scanner **10** has eleven detector modules. However, a different number of detector modules can be used. The invention does not depend on the number of detector modules in the ring **12**. It is topologically convenient, however, to have an odd number of detector modules.

In FIG. **6**, the slave notifies the master of an event but withholds the information about the event until the master actually requests that information. This minimizes the probability that the third data link will be busy ferrying data packets from the slave to the master, thereby minimizing the probability that a data packet will be dropped. However, it also imposes some additional complexity since the master must now request data packets of interest.

Alternatively, the slave sends the master a data packet for each event detected at that slave's associated detector module. If the master does not consider the event to be part of a coincidence, it simply discards the data packet. This eliminates the need for the second data link since the master no longer has to signal the slave to send a data packet.

Referring back to FIGS. 2-3, each detector block **17** also includes wavelength-shifting optical fibers **54** extending parallel to the major axis of each row of pillars on the scintillator block **21**. The fibers **54** are spread across the face of the scintillator block **21** nearest the object being imaged, as shown in FIG. 3, with one fiber **54** extending parallel to the major axis of each row of pillars **23**. Each fiber **54** is in optical communication with a detector **55** that provides a signal to a respective processor **18A-K**.

The walls of the fibers **54** are transparent to light emerging from the pillars **23**. As a result, light that originates in one of the pillars **23** (the shaded pillar in FIG. 3) adjacent

to a fiber **54** will introduce light into that fiber **54**. A portion of this light is trapped within the fiber **54** and guided to the detector associated with that fiber **54**. By observing the spatial distribution of light across the detectors, and hence across the fibers **54**, the processor **18A-K** can determine from which row of pillars **23** of the scintillator block **21** the light originated. A PET scanner incorporating a ribbon of fibers **54** in this manner is fully described in U.S. Patent No. 5,600,144, the contents of which are herein incorporated by reference in their entirety.

The fibers **54** extending across the scintillator blocks **21** provide information on only one of the two spatial coordinates required to identify the particular pillar **23** within the scintillator block **21** from which scintillation photons were emitted. A second coordinate is determined by the spatial distribution of light received by the photomultiplier tubes **19A-D**.

The spatial resolution in the second coordinate depends, in part, on the number of photomultiplier tubes **19A-D**. Because of the expense of photomultiplier tubes, it is desirable to reduce the number of photomultiplier tubes while maintaining adequate spatial resolution. This is achieved by a providing a light mixer **56** positioned between the photomultiplier tubes **19A-D** from the scintillator block **21**.

The light mixer **56** is a layer of optically transparent material. An interface **59** between the scintillator block **21** and the light mixer **56** can be coated with an index-matching layer to reduce reflections at that interface **59**. Similarly, an interface **57** between the light mixer **56** and the photomultiplier tubes **19A-D** can be coated with an index-matching layer to reduce reflections at that interface **57**.

A gamma ray photon entering a pillar **23** generates an isotropic spray of scintillation photons. These scintillation photons are scattered or reflected by structures within the optical element. Depending on which pillar the scintillation photons originate from, different numbers of scintillation photons strike the photomultiplier tubes **19A-D**. As a result, the first, second, third and fourth photomultiplier tubes **19A-D** generate corresponding first, second, third and fourth photomultiplier signals that depend on the number of scintillation photons detected by that photomultiplier tube **19A-D**.

Ideally, the ratio of the sum of the first and third photomultiplier signals and the sum of all four photomultiplier signals depends linearly on the value of the second coordinate associated with the pillar **23** that emitted the light. Similarly, the ratio of the sum of the first and second photomultiplier signals and the sum of all four photomultiplier signals depends linearly on the value of the first coordinate associated with the pillar **23** that emitted the light. Exemplary ideal ratios are shown by the solid lines **58, 60** in FIGS. 8A and 8B. In addition, the sum of all four photomultiplier signals should be the same, no matter which pillar **23** emits the light, as shown by the solid line **62** in FIG. 8C.

The shape of the curves shown in FIGS. 8A-C can be controlled, to some extent, by changing the properties of the light mixer **56**. For example, in the case of the light mixer of **56**, which is a layer of transparent material, there is a tendency for the ratio to be sigmoidal and for the sum to exhibit crowning, as shown by the dashed lines **64, 66, 68** in the three graphs of FIG. 8A-C.

In principle, if one knew the shape of the dashed lines **64, 66, 68**, one could compensate for non-linearity and crowing by creating a look-up table during a calibration procedure. Entries in the look-up table would correctly map a measured value to a coordinate associated with the emitting pillar **23**. However, to avoid the need to create a look-up table, and to thereby simplify the calibration procedure, it is desirable to avoid both non-linearity and crowning.

To avoid both non-linearity and crowning, a preferred optical element **70**, shown in FIG. 9, includes a mixing layer **72** adjacent to the scintillator block **21**, an unstructured cap layer **74** adjacent to the photomultiplier tubes **19A-D**, a structured outer layer **76** adjacent to the cap layer **74**, and a structured inner layer **78** between the mixing layer **72** and the structured outer layer **76**. The three layers are all made of an optically transparent medium.

The mixing layer **72** of the optical element **70** is a layer of transparent material between approximately 0.05 and 0.12 inches thick, and preferably 0.06 inches thick. This

mixing layer **72** permits light to mix freely for a short distance before entering the structured inner layer **78**.

Referring to FIG. 10, one embodiment of the structured inner layer **78** includes an optically transparent central region **80** having an outer wall **82** extending parallel to the sides of the optical element **70** and an optically transparent peripheral region **84A** adjacent to a perimeter **85** of the structured inner layer **78**. The peripheral region **84A** has an inner wall **86** extending parallel to, but spaced apart from, the outer wall **82** of the central region **80**. The inner and outer walls **86, 82** thus define a gap **88** that separates the central region **80** from the peripheral region **84A**. The gap **88** can be filled with air or a material having an index of refraction different from that of the optically transparent medium, thereby promoting total internal reflection within the central region **80** and the peripheral region **84A**. The width of the gap **88** is not critical, however it should be greater than a wavelength to suppress coupling across the gap **88**.

In general, it is desirable for a scintillation photon to proceed from the pillar **23**, directly across both the structured inner layer **78** and the structured outer layer **76**, and into the photomultiplier tube **19B** closest to the pillar. This will provide the most accurate indication of the location of the gamma ray event that resulted in that scintillation photon. However, in the embodiment shown in FIG. 10, it is possible for a scintillation photon entering the peripheral region **84A** from a pillar **23** to reflect off the inner wall **86** several times, thereby causing it to traverse a circuitous route that takes it far away from its point of entry into the peripheral region **84A**. In so doing, such a photon may not reach a photomultiplier tube **19A-D** until it has traveled some distance, along a circuitous route, from that pillar **23**. In many cases, this causes the scintillation photon to exit the structured outer layer **76** at a point far away from where it entered the structured outer layer **76**.

To prevent the scintillation photons from straying too far from their origins, embodiments such as those shown in FIGS. 11 and 12 surround the central region **80** with several peripheral regions **84A-D, 84A-H**, each of which is adjacent to a portion of the optical element's perimeter **85**. Each of the peripheral regions **84A-D, 84A-H** is

separated from neighboring peripheral regions by inner and outer walls **82, 86** having optical properties like those discussed in connection with FIG. 10. These walls trap the scintillation photons, thereby preventing them from straying too far from the pillar **23** in which they were generated.

The structured outer layer shown FIG. 12 contains more distinct peripheral regions 84A-H than does the structured outer layer shown in FIG. 11. For this reason, the structured outer layer of FIG. 12 more effectively confines scintillation photons than does the structured outer layer of FIG. 11.

The gap **88** can be spaced apart from the walls of the optical element **70** so as to coincide with the boundaries of the pillars **23** that lie underneath the peripheral region **84A**. This is advantageous because all photons emerging from the same pillar will then be subjected to the same physical environment. However, this is not required. The gap **88** can, for example, bisect a pillar **23**.

The inner wall **86** of the peripheral region **84A** is highly polished, so that scintillation photons in the peripheral region **84A** that are incident on the inner wall **86** are specularly reflected. In contrast, the outer wall **82** of the central region **80** is roughened, so that scintillation photons in the central region **80** that are incident on the outer wall **82** are reflected in a random direction. As a result, the probability that a scintillation photon in the peripheral region **84A** will reach the photomultiplier tube is greater than the probability that a scintillation photon in the central region **80** will reach the photomultiplier tube. This tends to enhance the response of the photomultiplier tubes **19** to scintillation photons in the peripheral region **84A** relative to the response of the photomultiplier tubes **19** to scintillation photons in the central region **80**.

The dashed line **68** in FIG. 8C can be interpreted as a probability density function indicative of the likelihood that a scintillation photon originating at a particular value of the second coordinate will reach a photomultiplier tube **19A-D**. In the conventional optical element, the probability density function **68** is non-uniform because scintillation photons originating in the central region **80** more likely to reach the photomultiplier tube **19A-D** than are scintillation photons originating in the peripheral region **84A**. The

structured inner layer **78**, by encouraging photons from the peripheral region **84A** to reach the photomultiplier tubes **19A-D** and simultaneously discouraging scintillation photons from the central region **80** from reaching the photomultiplier tubes **19A-D**, tends to flatten the probability density function **68**. This tends to make the sum of the first and second photomultiplier signals independent of the second coordinate.

The structured outer layer **76** is intended to cause the photomultipliers to collectively respond as shown in FIGS. 8A and 8B. Such a linear response is desirable because it simplifies the task of calibrating the photomultipliers. Referring now to FIG. 13, the structured outer layer **76** of the optical element **70** is made up of four optically transparent quadrants **90A-D**, one corresponding to each photomultiplier tube **19A-D**. Each quadrant **90A-D** has two outer walls **92A, 92B** that meet at an exterior corner **94A** and two inner walls **96A, 96B** that meet at an interior corner **98A**. The inner walls **96A, 96B** of each quadrant **90A-D** are highly polished so that scintillation photons incident thereon are specularly reflected.

Collectively, the inner walls **96A, 96B** of all four quadrants **90A-D** form a cruciform gap **100** extending in the directions of both the major axis and the minor axis. The gap **100** can extend all the way across the structured outer layer **76** as shown in FIG. 13, only part way across in both directions, as shown in FIG. 14, or part way across in one direction and all the way across in the other direction, as shown in FIG. 15.

The cruciform gap **100** can be filled with air or a material having an index of refraction different from that of the optically transmitting medium, thereby promoting total internal reflection within each quadrant **90A-D**. The width of the gap **100** is not critical, however it should be greater than a wavelength to suppress coupling across the gap **100.**

For example, in one embodiment, the structured inner layer **78** is 0.923 inches (16.8 mm) thick and the total thickness of the optical element **70** is 1.573 inches (39.9 mm). An optically transmissive layer **102**, like the mixing layer **72**, is optionally placed between the structured outer layer **76** and the structured inner layer **78**. This optional layer **102** is approximately .15 inches (3.8 mm) thick. The length and width of the optical

element **70** are 3.21 inches (81.8 mm) and 2.695 inches (94.4 mm) respectively. The cap layer **74** of optically transparent material can be placed over the structured outer layer **76**, thereby preventing foreign matter from falling into the cruciform gap **100**. This cap layer **74** is between 0.06 inches and 0.12 inches.

In the embodiment described herein, there are four photomultiplier tubes **19A-D** arranged in a grid. Hence, there are four regions **90A-D** within the structured outer layer **76**. The regions are disposed on the structured outer layer **76** so that each region **90A** faces one **19A** of the four photomultiplier tubes **19A-D**. The resulting gap between the regions is thus a cruciform gap **100**.

In other embodiments, there may be more than four photomultiplier tubes arranged in a rectangular array. In such cases, there will be a corresponding number of regions within the structured outer layer **76**, with each region facing a corresponding photomultiplier tube. The resulting gap between regions will then define a grid. The walls defining the gap are highly polished so that scintillation photons incident on a wall from a particular region are specularly reflected back into that region.

In embodiments having many photomultiplier tubes, an structured inner layer **78** can have several nested peripheral regions surrounding the central region. These additional regions are shaped like the peripheral region and are separated from each other by gaps. Each gap has an inward-facing wall and an outward-facing wall. The inward-facing wall is roughened to discourage specular reflection and the outward-facing wall is highly polished to encourage specular reflection. The degree of roughening and polishing of each pair of inward-facing and outward-facing walls can change from one pair to the next, thereby enabling one to tune the structured inner layer to achieve the flattest possible response.

In some embodiments, a mask placed between the structured outer layer **76** and the photomultiplier tubes **19A-D** covers selected portions of the structured outer layer **76**. An exemplary mask **104**, shown in FIG. 16, has openings **106A-D** sized to correspond to the photomultiplier tubes **19A-D**. These openings **106A-D** allow passage of scintillation photons only from directly beneath each photomultiplier tube **19A-D**. Scintillation

photons that would otherwise emerge between photomultiplier tubes **19A-D** are blocked by the mask **104**.

Scintillation photons that would otherwise reach the photomultiplier tubes from regions of the structured outer layer **76** that lie between the photomultiplier tubes **19A-D** are often those that have undergone multiple reflections. As a result, these scintillation photons no longer provide information indicative of their origins. To more efficiently absorb these scintillation photons, the mask **104** can be made black.

The optical element **70** can be formed by casting a single monolithic block integrating the individual layers. Alternatively, the optical element **70** can be formed by casting the individual layers. The layers are then glued together with an index matching adhesive between the layers. In either case, removal of the structured outer layer **76** and the structured inner layer **78** from the mold is facilitated by providing rectangular and cruciform gaps **88,100** having a V-shaped profile.

Having described the invention, and a preferred embodiment thereof, what we claim as new and secured by letters patent is:

CLAIMS

1. A PET scanner comprising:

a scintillator block;

a plurality of photodetectors;

an optical element disposed between the scintillator block and the plurality of photodetectors, the optical element having:

a first layer that includes a central region having an outer wall and a peripheral region having an inner wall, the inner and outer wall being separated by a first gap; and

a second layer in optical communication with the first layer, the second layer including at least a first region and a second region, the first region having a first interior wall and the second region having a second interior wall opposite the first interior wall, the first and second interior walls being separated by a second gap.

2. The PET scanner of claim 1, wherein the first layer comprises a perimeter wall, and the peripheral region is adjacent to at least a portion of the perimeter wall.

3. The PET scanner of claim 1, wherein the peripheral region is adjacent to the entire perimeter wall.

4. The PET scanner of claim 1, further comprising one or more additional peripheral regions, the one or more additional peripheral regions being adjacent to a portion of the perimeter wall that is not adjacent to the peripheral region.

5. The PET scanner of claim 4, wherein an additional peripheral region is separated from the peripheral region by a gap.

6. The PET scanner of claim 5, wherein the gap extends to the perimeter wall.

7. The PET scanner of claim 1, wherein the inner wall and the outer wall have different optical characteristics.

8. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is polished and the other is unpolished.

9. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is opaque and the other is not opaque.

10. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is black and the other is not black.

11. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is transparent and the other is not transparent.

12. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is translucent and the other is not translucent.

13. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is absorbtive and the other is not absorbtive.

14. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is configured to cause a specular reflection and the other is cause a reflection other than a specular reflection.

15. The PET scanner of claim 14, wherein the one of the inner wall and the outer wall that is configured to cause a specular reflection comprises a metal coating.

16. The PET scanner of claim 14, wherein the one of the inner wall and the outer wall that is configured to cause a specular reflection comprises a reflective coating.

17. The PET scanner of claim 14, wherein the one of the inner wall and the outer wall that is configured to cause a specular reflection has an index of refraction selected to cause total internal reflection of light incident thereon.

18. The PET scanner of claim 7, wherein one of the inner wall and the outer wall is configured to cause a diffuse reflection and the other is cause a reflection other than a diffuse reflection.

19. The PET scanner of claim 18, wherein the one of the inner wall and the outer wall that is configured to cause a diffuse reflection comprises a plastic coating.

20. The PET scanner of claim 18, wherein the one of the inner wall and the outer wall that is configured to cause a diffuse reflection comprises a coating of paint.

21. The PET scanner of claim 18, wherein the one of the inner wall and the outer wall that is configured to cause a diffuse reflection has a roughened surface.

22. The PET scanner of claim 7, wherein a surface of the inner wall is polished.

23. The PET scanner of claim 7, wherein an inner surface of the outer wall is roughened.

24. The PET scanner of claim 1, wherein the optical element further comprises a third layer disposed adjacent to the scintillator block.

25. The PET scanner of claim **1**, wherein the first gap has an optical property that is different from a corresponding optical property of the central region and the peripheral region.

26. The PET scanner of claim **25**, wherein the first gap comprises an air gap.

27. The PET scanner of claim **1**, wherein one of the first interior wall and the second interior wall is polished and the other is unpolished.

28. The PET scanner of claim **1**, wherein one of the first interior wall and the second interior wall is opaque and the other is not opaque.

29. The PET scanner of claim **1**, wherein one of the first interior wall and the second interior wall is black and the other is not black.

30. The PET scanner of claim **1**, wherein the first interior wall and the second interior wall are specularly reflecting walls.

31. The PET scanner of claim **1**, wherein the second gap defines a grid of regions.

32. The PET scanner of claim **31**, wherein the second gap extends across the second layer.

33. The PET scanner of claim **31**, wherein the second gap extends part way across the second layer.

34. The PET scanner of claim **1**, wherein the opposed first and second interior walls are parallel.

35. The PET scanner of claim **1**, wherein the opposed first and second interior walls are not parallel.

36. The PET scanner of claim **31**, wherein each region in the grid of regions is positioned to correspond to a photodetector from the plurality of photodetectors.

37. The PET scanner of claim **1**, wherein the second gap is a cruciform gap.

38. The PET scanner of claim **37**, wherein the cruciform gap comprises intersecting first and second arms, at least one of the first and second arms extending across the second layer.

39. The PET scanner of claim **37**, wherein the cruciform gap comprises intersecting first and second arms, the first and second arms extending part way across the second layer.

40. The PET scanner of claim **1**, further comprising a mask disposed to prevent scintillation photons emerging from selected portions of the optical element from reaching the photodetectors.

41. The PET scanner of claim **40**, wherein the mask comprises regions forming apertures at locations opposite the photodetectors.

42. The PET scanner of claim **40**, wherein the mask is disposed between the optical element and the photodetectors.

43. The PET scanner of claim **40**, wherein the mask is absorbtive.

44. The PET scanner of claim **40**, wherein the mask is reflective.

45. The PET scanner of claim **44**, wherein the mask is specularly reflective.

46. The PET scanner of claim **44**, wherein the mask is diffusely reflective.

47. An optical element for directing light from a scintillator block to a plurality of photodetectors, the optical element comprising:

a first layer in optical communication with the scintillator block, the first layer having a central region having an outer wall and a peripheral region having an inner wall, the inner and outer wall being separated by a first gap; and

a second layer in optical communication with the plurality of photodetectors and with the first layer, the second layerincluding at least a first region and a second region, the first region having a first interior wall and the second region having a second interior wall opposite the first interior wall, the first and second interior walls being separated by a second gap.

48. The optical element of claim **47**, wherein the inner wall and the outer wall are configured such that a photon incident on the inner wall from the peripheral region encounters a first reflection coefficient that is greater than a second reflection coefficient encountered by a photon incident on the outer wall from the central region.

49. The optical element of claim **47**, wherein an inner surface of the inner wall of the peripheral region has a greater reflection coefficient than an inner surface of the outer wall of the central region.

50. The optical element of claim **49**, wherein the inner surface of the inner wall is polished.

51. The optical element of claim **49**, wherein the inner surface of the outer wall is roughened.

52. The optical element of claim **47**, wherein the optical element further comprises a third layer disposed facing the scintillator block.

53. The optical element of claim **47**, wherein the first gap comprises an air gap.

54. The optical element of claim **47**, wherein the first interior wall and the second interior wall are specularly reflecting walls.

55. The optical element of claim **47**, wherein the second gap defines a grid of regions.

56. The optical element of claim 55, wherein each region in the grid of regions is positioned to correspond to a photodetector from the plurality of photodetectors.

57. The optical element of claim 47, wherein the second gap is a cruciform gap.

58. A PET scanner comprising:

a scintillator block for generating a spatial light distribution of scintillation photons in response to illumination by a gamma ray photon;

means for an outer and inner the spatial light distribution of scintillation photons to generate a modified spatial light distribution; and

a plurality of photodetectors for receiving the modified spatial light distribution from the outer and inner means.

59. An optical element for directing light from a scintillator block to a plurality of photodetectors, the optical element comprising:

a structured outer layer in optical communication with the scintillator block; and

a structured inner layer in optical communication with the plurality of photodetectors.

60. A PET scanner comprising:

a scintillator block;

a plurality of photodetectors;

an optical element as recited in claim **59**, the optical element being disposed between the scintillator block and the plurality of photodetectors.

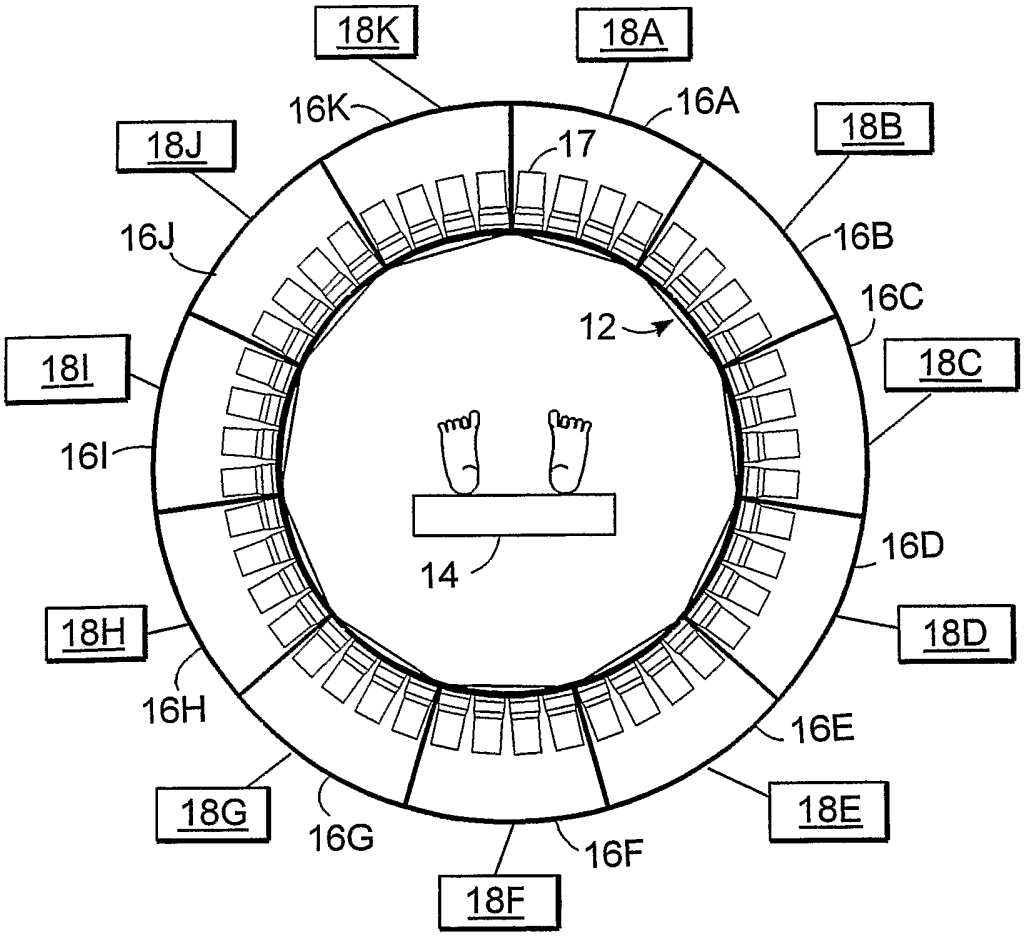
18K
18A
16K
16A
18J
17
18B
16J
16B
16C
12
18I
18C
16I
16D
14
18H
18D
16H
16E
18G
18E
16G
16F
18F

FIG. 1

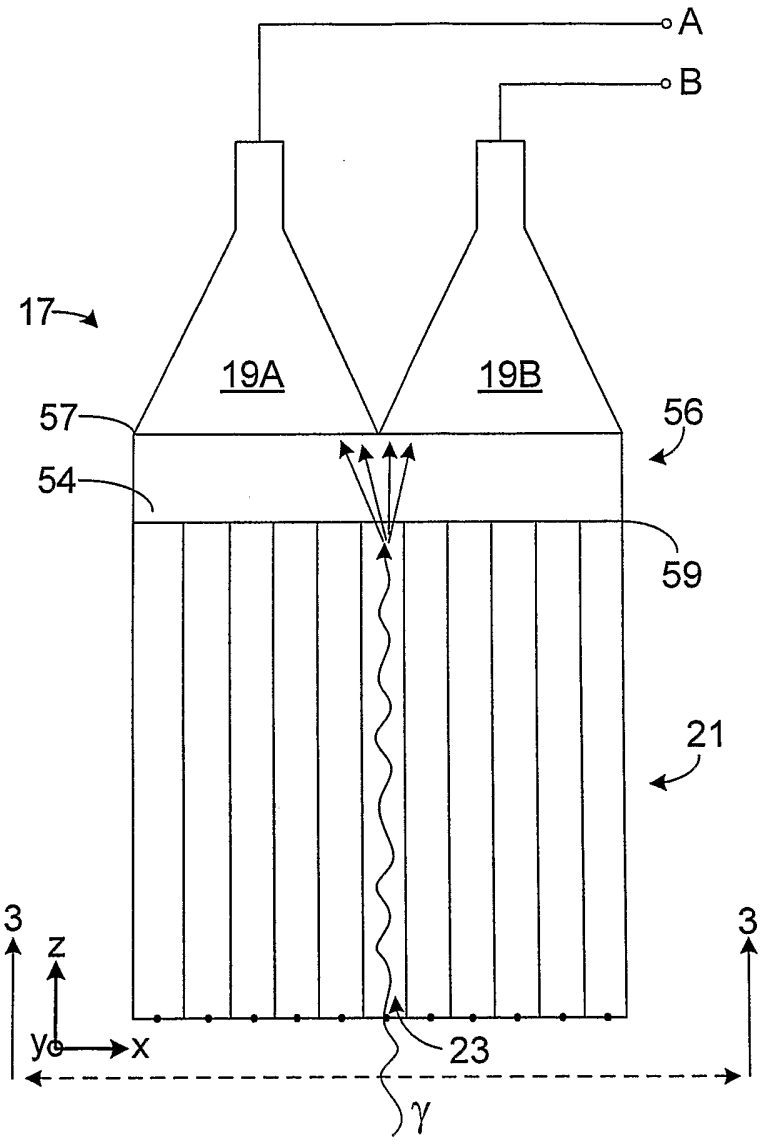

FIG. 2A

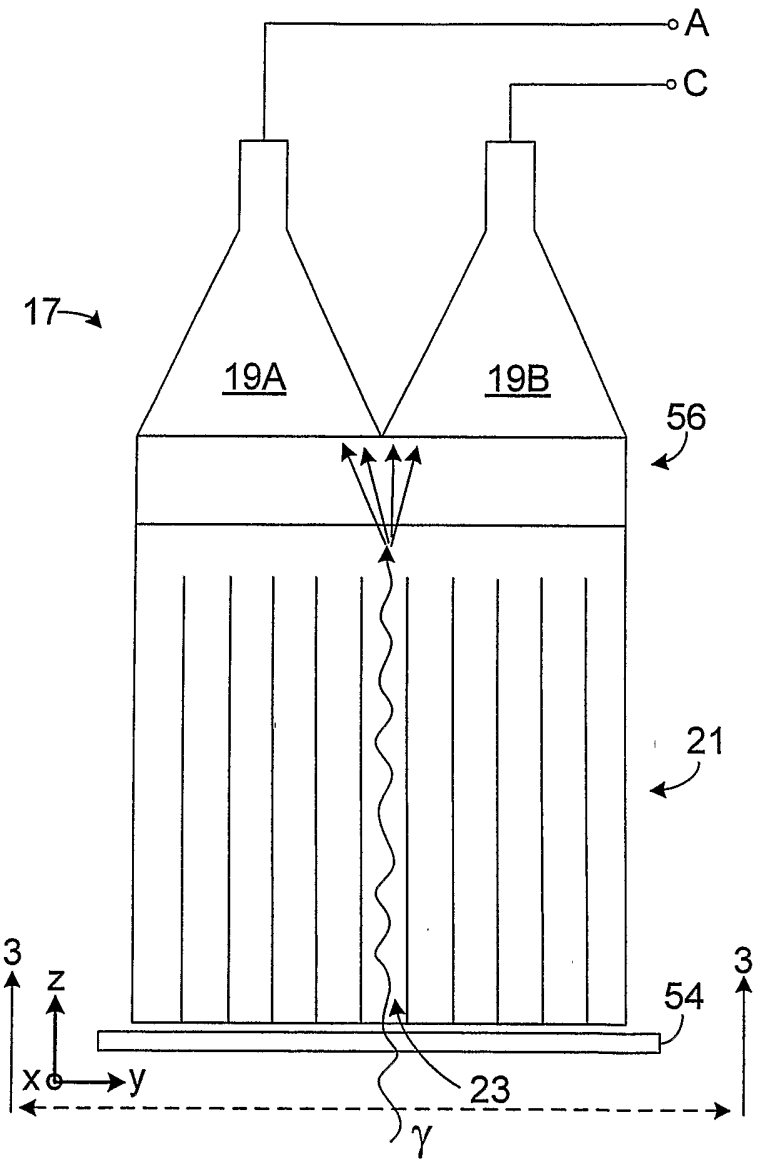

FIG. 2B

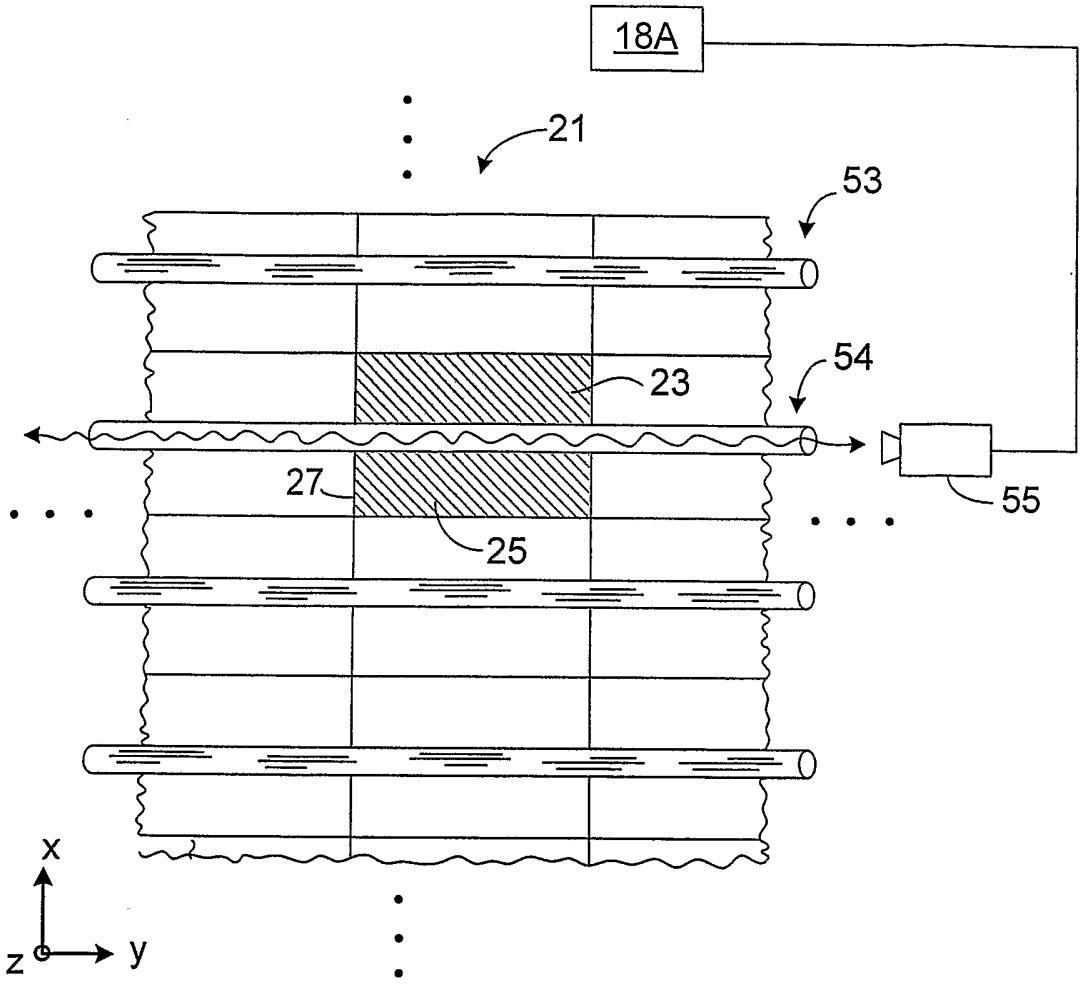

FIG. 3

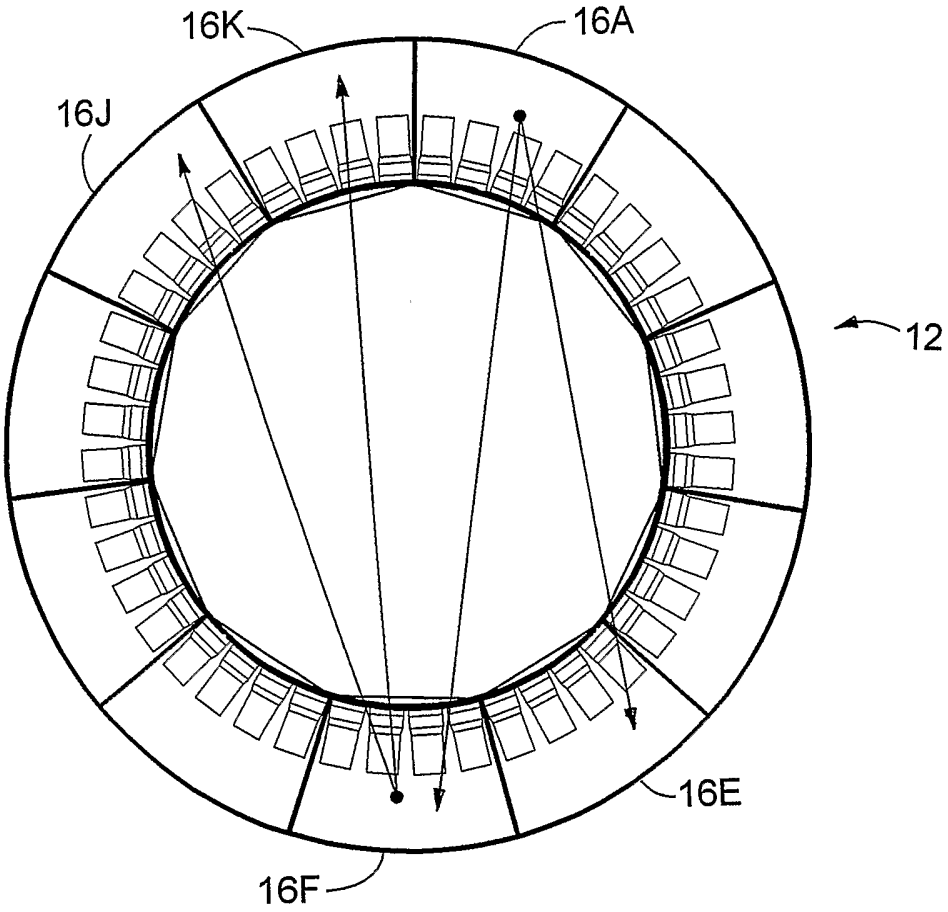

FIG. 4

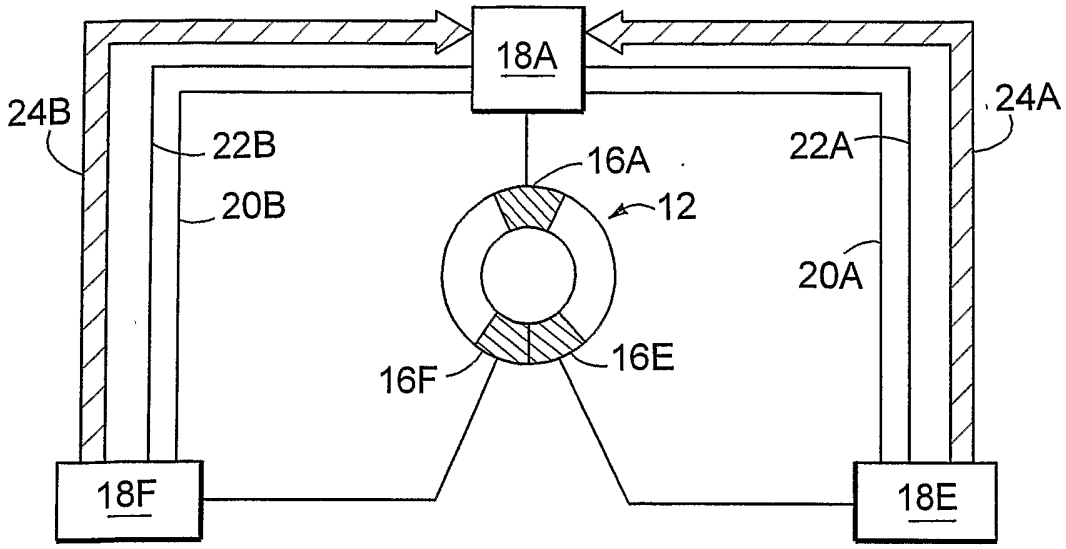

FIG. 5

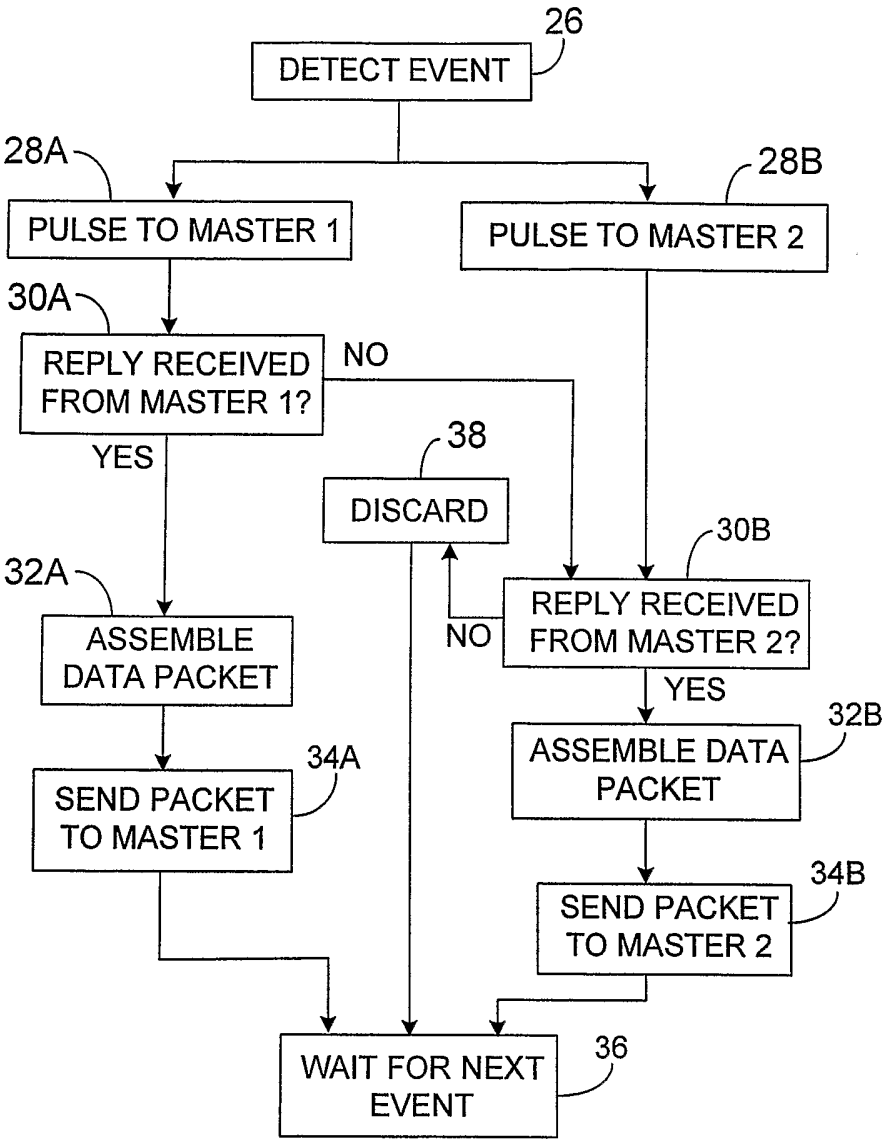
26
DETECT EVENT
28A
28B
PULSE TO MASTER 1
PULSE TO MASTER 2
30A
REPLY RECEIVED FROM MASTER 1?
NO
YES
38
DISCARD
30B
32A
ASSEMBLE DATA PACKET
NO
REPLY RECEIVED FROM MASTER 2?
YES
32B
ASSEMBLE DATA PACKET
34A
SEND PACKET TO MASTER 1
34B
SEND PACKET TO MASTER 2
WAIT FOR NEXT EVENT
36

FIG. 6

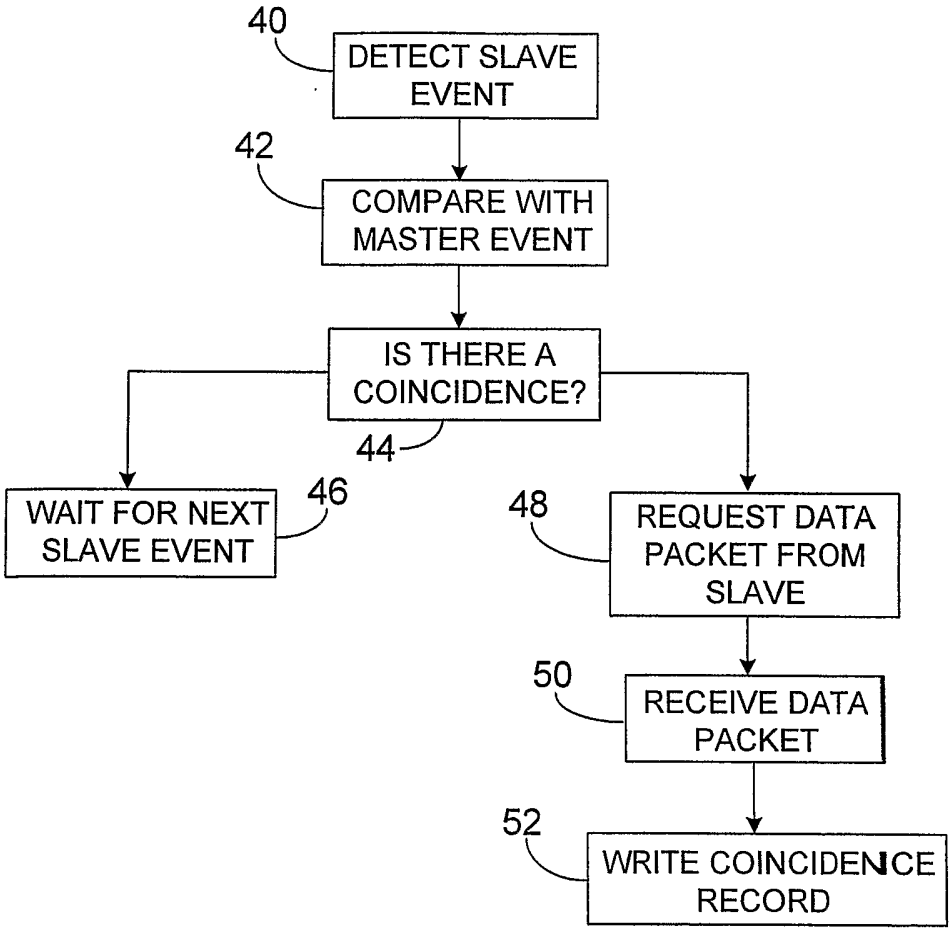
40
DETECT SLAVE EVENT
42
COMPARE WITH MASTER EVENT
IS THERE A COINCIDENCE?
44
46
WAIT FOR NEXT SLAVE EVENT
48
REQUEST DATA PACKET FROM SLAVE
50
RECEIVE DATA PACKET
52
WRITE COINCIDENCE RECORD

FIG. 7

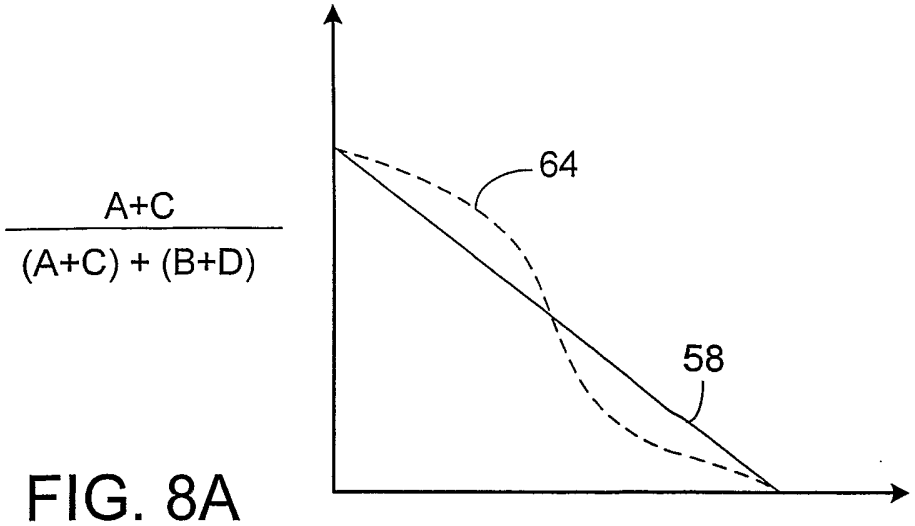

FIG. 8A

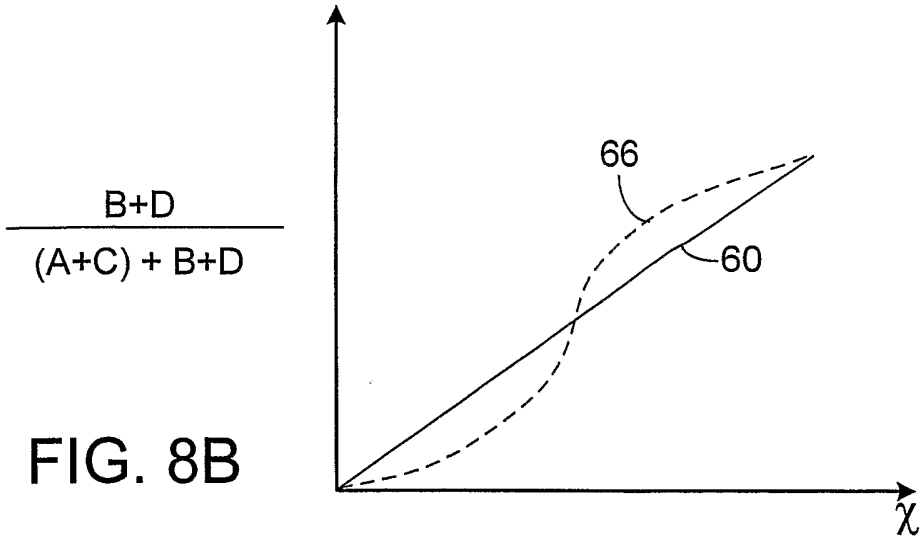

FIG. 8B

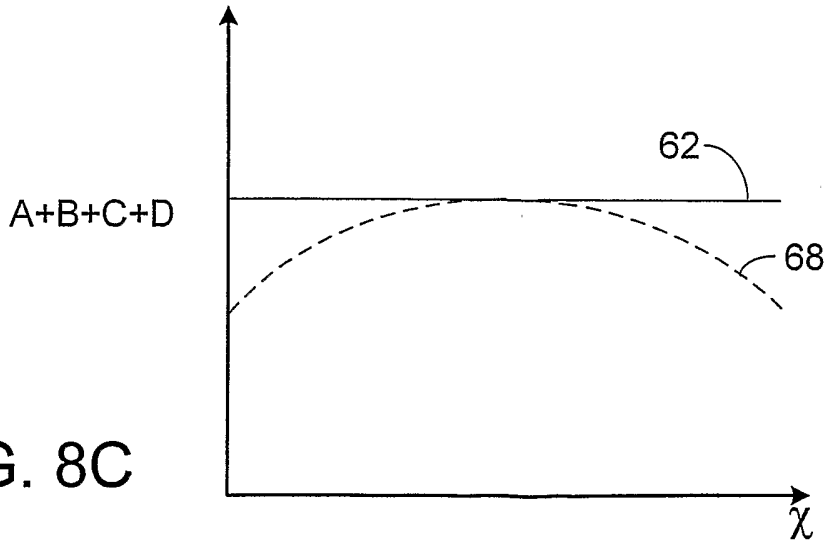

FIG. 8C

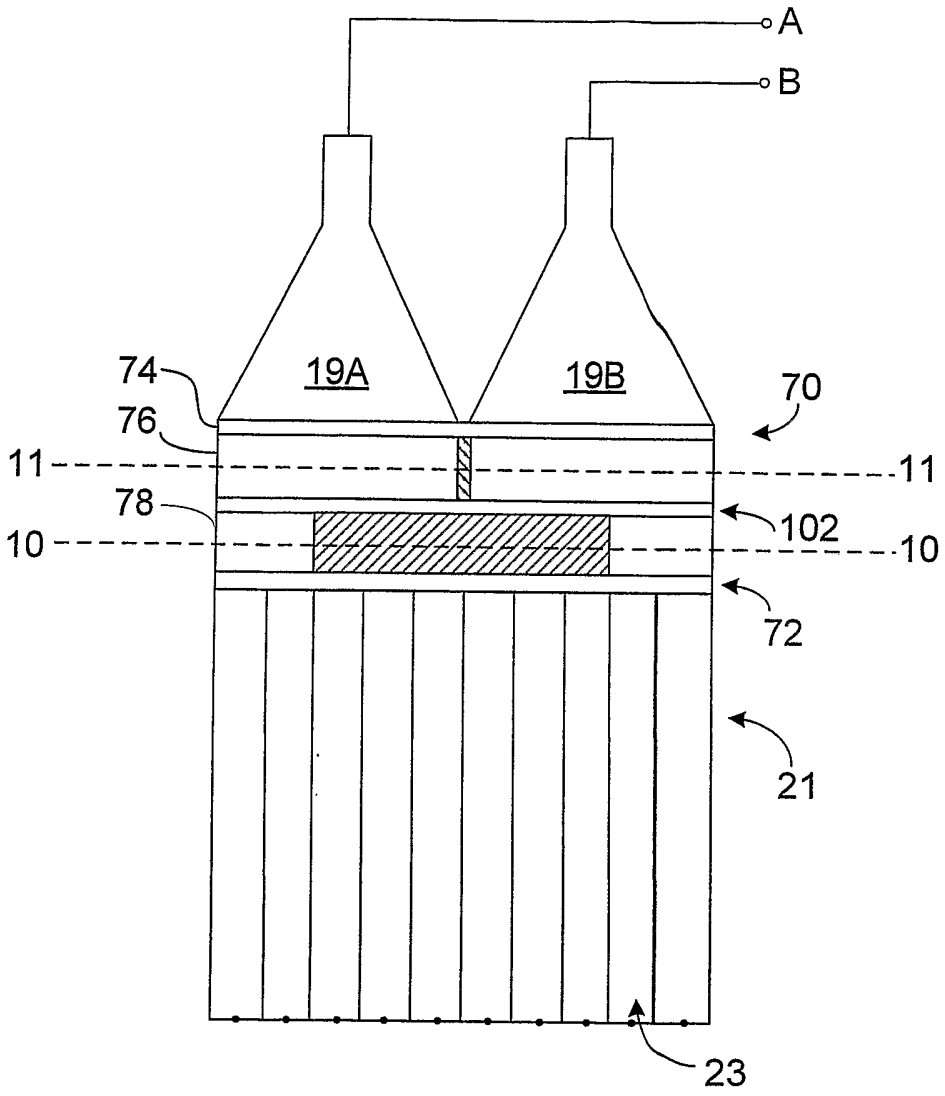

FIG. 9

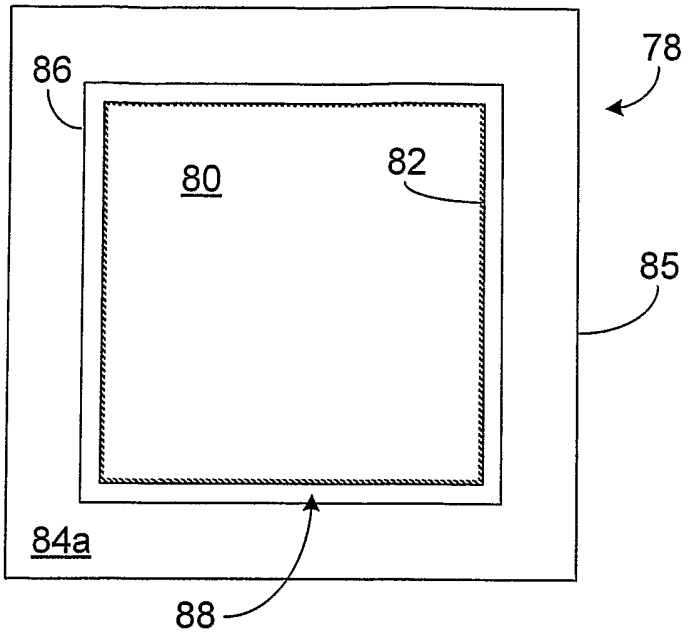

FIG. 10

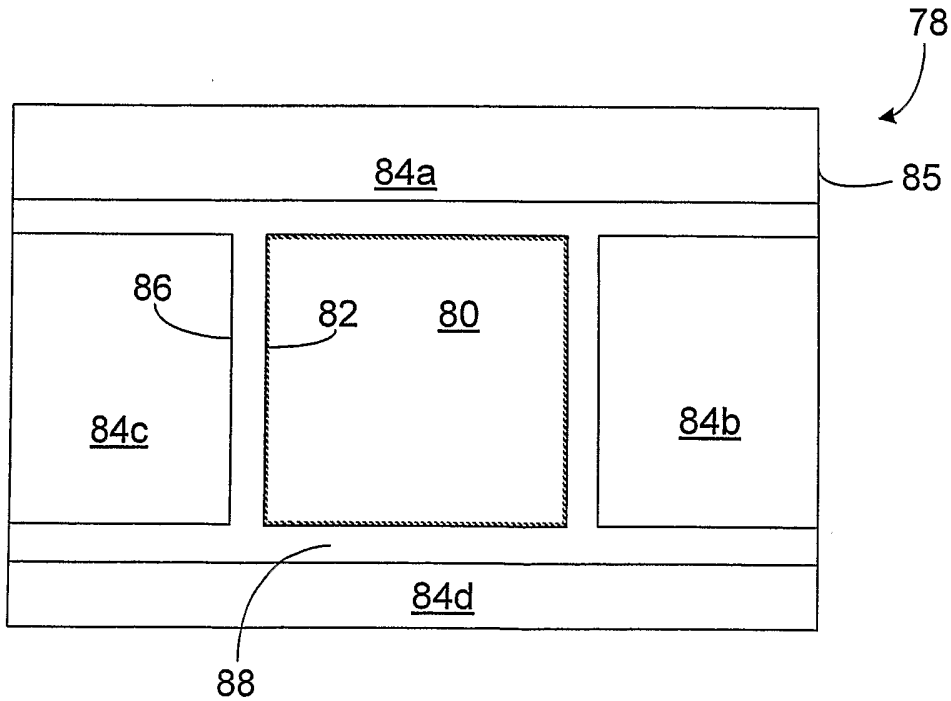

FIG. 11

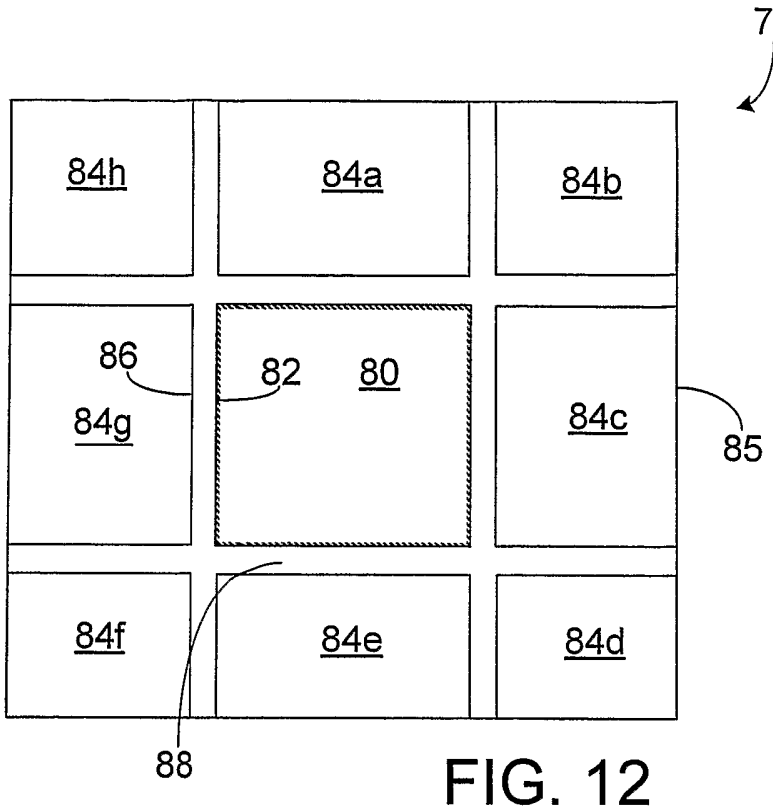
78
84h
84a
84b
86
82
80
84g
84c
85
84f
84e
84d
88

FIG. 12

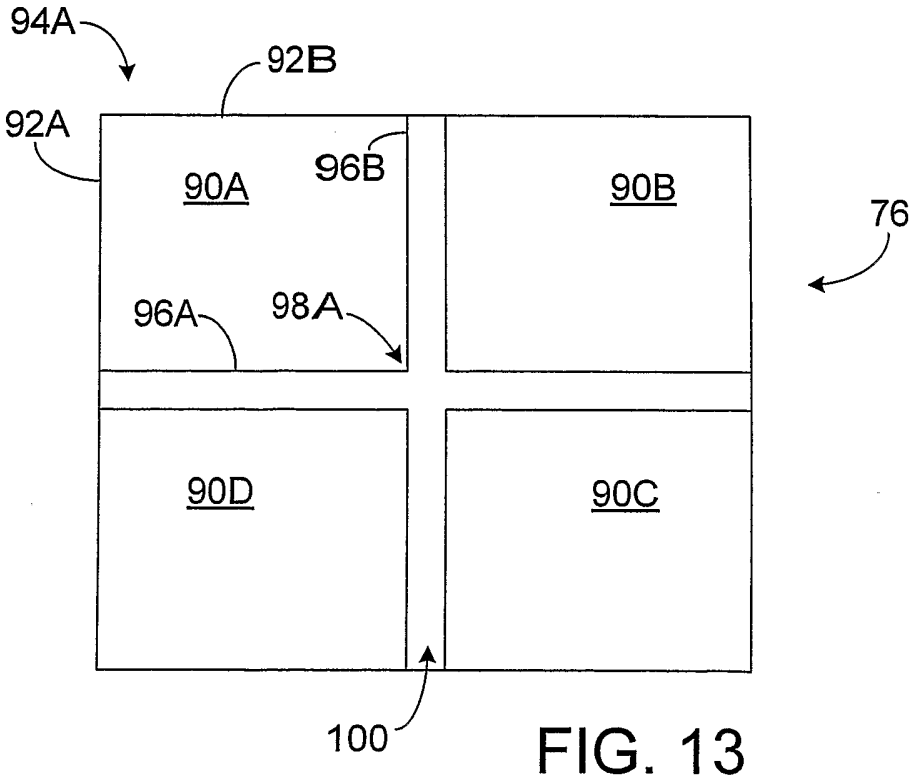
94A
92B
92A
90A
96B
90B
76
96A
98A
90D
90C
100

FIG. 13

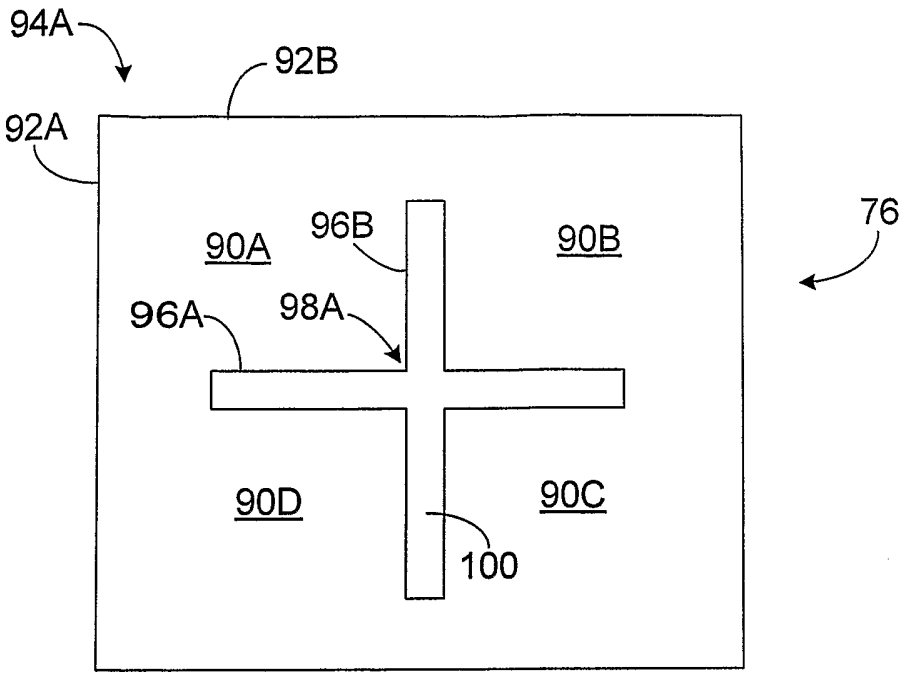
94A
92B
92A
96B
90A
90B
76
96A
98A
90D
90C
100

FIG. 14

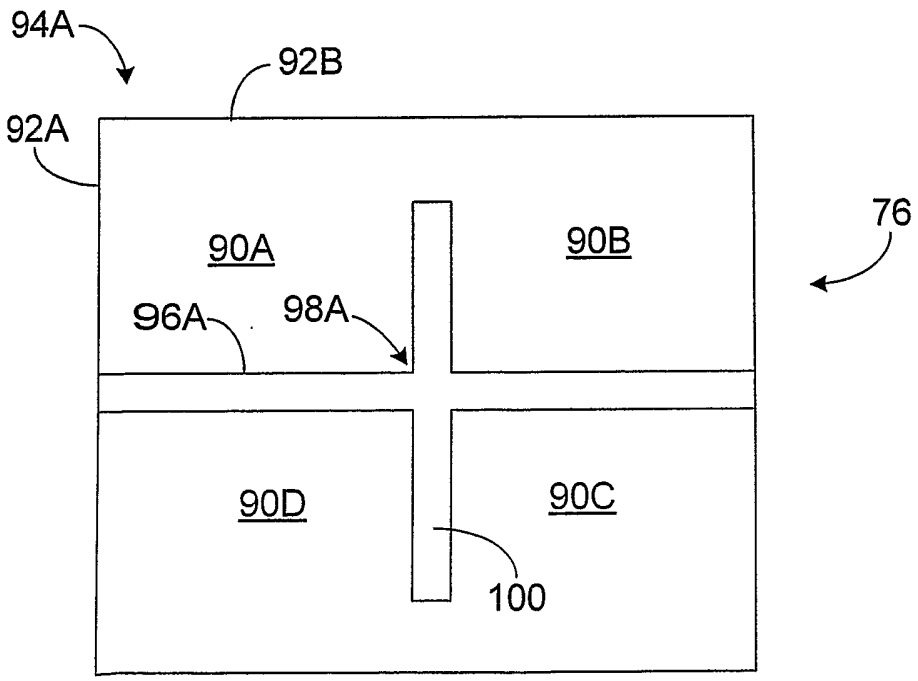
94A
92B
92A
76
90A
90B
96A
98A
90D
90C
100

FIG. 15

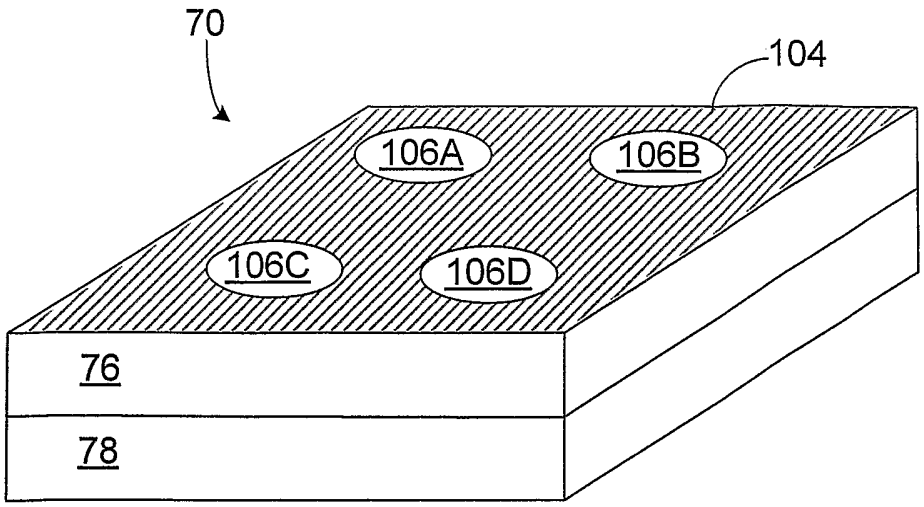

FIG. 16