

LOCALIZED RADIATION SENSING AND REPORTING SURFACES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present invention claims the benefit of U.S. Provisional Application Serial No. 62/991,644, filed March 19, 2020.

BACKGROUND

[0002] Human health risk associated with radiation exposure is a well-studied field. The US Nuclear Regulatory Commission (NRC) has established dose limits for various body regions and recommends several radiation sensor types. However, currently available sensors are limited in functionality. There is no protective covering that detects and instantaneously reports the quantitative exposure to radioactivity for a specific location over a large surface area. Personal dosimeters exist, but these are typically passive detectors that are measured retrospectively. Other types of electronic devices may give immediate audible feedback, but only at one location. Those working in high radiation environments, including fluoroscopy staff and nuclear power workers, must therefore be vigilant about direct and scattered radiation because it is difficult to know precisely where they are being exposed. Thus, there is an ongoing need for a detector that comprehensively detects and/or reports the location of radiation exposure to a large surface area in real time.

BRIEF SUMMARY

[0003] The Summary is provided to introduce a selection of concepts that are further described below in the Detailed Description. This Summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

[0004] There is currently no detector or protective covering that detects, quantifies, and instantaneously reports exposure to radioactivity over a large surface area, such as on the area of the protective gear used by clinical fluoroscopy staff or other radiation workers. The present disclosure addresses at least some of these and other challenges through devices and systems for detecting general-area radiation exposure. For example, through the described devices and systems

it is possible to make radiation “visible” so that occupational workers can react in real-time, thereby minimizing their exposures.

[0005] An article is provided that includes a substrate, a plurality of radiation sensors, each radiation sensor of the plurality of radiation sensors being disposed at a corresponding position on the substrate; and alert circuitry coupled to the plurality of radiation sensors, wherein the alert circuitry indicates, in real time, a localized detection of radiation according to corresponding one or more positions on the substrate of a particular one or more radiation sensors of the plurality of radiation sensors.

[0006] One aspect of the present disclosure provides such an article, which can be referred to as a Smart Radiation Sensing and Reporting Surface (SRSRS). The SRSRS is a lightweight, self-contained, flexible covering that can be used in various radiation-based settings where ionizing radiation is used. The SRSRS can be integrated into radiation protective garments, such as those used in fluoroscopy suites, or the SRSRS can be formed as a sheet-like material and placed over equipment or on the ground where radiation spills or inadvertent radiopharmaceutical contamination has occurred. In real time, the article detects the locus of intense radiation on various locations, such as on the wearer’s body or in a spill on the floor, and reports the location with, for example, light-emitting-diode (LED) signals that are easily visible by those in the vicinity of the article.

[0007] Potential applications include real-time, precise location monitoring of clinic workers, detection of existing radiation spills, and worker training, among others. The system could be utilized in radiation-hazardous environments, enabling immediate feedback via any suitable communication technologies and logged exposures for real-time or retrospective analysis of ALARA (as low as reasonably achievable) exposures. Additionally, the article could be used by nuclear power workers (or others in relatively high radiation environments) exposed to various ionizing radiation environments and hazards, and the military for use, such as defense and shielding, and monitoring against potential radiological or nuclear threats.

[0008] In sheet form, the article can be draped over a surface in order to detect radiation either impinging on or emanating from the surface, depending on the orientation of the sheet. For example, the article can be placed onto radiation-contaminated surfaces with the radiation detector directed inward toward the surface, in order to identify the location of a spilled source on the surface. Alternately, the detectors can be oriented outwardly to detect external radiation and

similarly draped over or integrated into equipment. In garment form, the article alerts radiation workers to ongoing radiation exposure, and hence can guide them to compensate their positioning (e.g., stance or proximity) to minimize or eliminate continued exposure. The article can be integrated into protective leaded aprons, skirts, and the like, which already exist in the clinic.

[0009] According to one aspect of the present disclosure, an SRSRS system uses the features of at least one scintillator (and corresponding scintillator detector), and reporter to determine and alert to the presence of radiation. The scintillator reacts to the presence of radiation with luminescence; the detector receives the light signal from the scintillator and communicates with the reporter; and the reporter then alerts the user to the presence of radiation. These three elements can be configured in various ways such that the strength and location of the detected radiation is known. Of course, implementations are not limited to scintillators (and corresponding detectors). For example, other suitable real-time-capable radiation detectors, such as solid-state devices, could be used in place of the scintillators/detectors and be configured to enable detection of strength/magnitude and location of detected radiation for appropriate alerting via the reporter(s).

DETAILED DESCRIPTION

[0010] The accompanying Figures are provided by way of illustration and not by way of limitation. The foregoing aspects and other features of the disclosure are explained in the following description, taken in connection with the accompanying example figures (also “FIG.”) relating to one or more embodiments, in which:

[0011] FIGs. 1A-1D illustrate iso-exposure fields overlaid over the more continuous exposure gradient with increasing distance for an occupational radiation worker during fluoroscopy procedures;

[0012] FIG. 2 is an example application of an SRSRS article as disclosed herein, used in a fluoroscopy suite;

[0013] FIGs. 3A and 3B show a perspective view and representative schematic, respectively, of an example article providing a localized radiation sensing and reporting surface;

[0014] FIG. 4 is a schematic representation of a radiation detection system according to one aspect of the present disclosure;

[0015] FIG. 5 shows an example of various fiber configurations of equivalent detection volumes;

- [0016] FIG. 6 shows an example of a portion of a detector configuration;
- [0017] FIGs. 7A and 7B illustrate configurations for a radiation detection system using a scintillation optical fiber mesh coupled to photosensors in one and two directions;
- [0018] FIGs. 8A-8C illustrate example article substrate configurations with scintillation optical fiber mesh;
- [0019] FIGs. 9A and 9B illustrate a detector configuration where a single scintillator and the detector are integrated and disposed directly in the unit area;
- [0020] FIGs. 10A-10C illustrate example article substrate configurations with individual region composites;
- [0021] FIGs. 11A and 11B illustrate a detector configuration where the scintillator, detector, and LED are integrated and disposed directly in the unit area;
- [0022] FIGs. 12A-12C illustrate example article substrate configurations with integrated elements;
- [0023] FIG. 13 is an example schematic of a layered SRSRS configuration showing various radiation interactions in different layers of the SRSRS;
- [0024] FIGs. 14A-14D illustrate example classical fiber weaves that can be used for a SOF mesh;
- [0025] FIGs. 15A and 15B illustrate light intensity characterizations;
- [0026] FIG. 16A shows a photograph of variously grouped fiber optic bundles of different fiber sizes;
- [0027] FIG. 16B shows various commercially available SiPM arrays and front-end electronics; and
- [0028] FIG. 17 illustrates a representative flexible LED panel for testing.

DETAILED DESCRIPTION

[0029] Localized radiation sensing and reporting surfaces are described. An article is provided that provides a localized detection of radiation according to corresponding one or more positions on a substrate of a particular one or more radiation sensors.

[0030] One aspect of the present disclosure provides such an article, which can be referred to as an SRSRS. The SRSRS is a lightweight, self-contained, flexible covering that can be used in various settings where ionizing radiation is used. The SRSRS can be integrated into radiation

protective garments, such as those used in fluoroscopy suites or sites containing nuclear or generator-produced radiation, or the SRSRS can be formed as a sheet-like material and placed over equipment or on the ground where radiation spills or inadvertent radiopharmaceutical contamination has occurred. In real time, the article detects the locus of intense radiation on various locations, such as on the wearer's body or in a spill on the floor, and reports the location with, for example, LED signals that are easily visible by those in the vicinity of the article. Haptics/stimulation or other signals may be used to directly inform a wearer of exposure. In some implementations, exposure information can further be recorded, relayed wirelessly, and/or displayed other ways or recorded for retrospective analysis, such as when training new medical residents or radiation workers.

[0031] For the purposes of promoting an understanding of the principles of the present disclosure, reference will now be made to certain embodiments and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the disclosure is thereby intended, such alteration and further modifications of the disclosure as illustrated herein, being contemplated as would normally occur to one skilled in the art to which the disclosure relates.

[0032] FIGs. 1A-1D illustrate iso-exposure fields overlaid over the more continuous exposure gradient with increasing distance for an occupational radiation worker during fluoroscopy procedures. Fluoroscopy staff must be vigilant about direct and scattered radiation and may not know where they are being exposed, particularly when in the midst of working with a patient at a fluoroscopic system.

[0033] Here, four orientations of a fluoroscopic system **100** and associated impact of exposure fields on a worker **105** are shown. Iso-exposure field lines **110** are indicated for each configuration: A is > 300 mR/hr; B is 100-500 mR/hr; C is 50-100 mR/hr; D is 25-50 mR/hr; E is 10-25 mR/hr; and F is < 10 mR/hr. The fluoroscopic system **100** involves an x-ray generator configured to direct x-rays through a patient on a table to an imaging detector.

[0034] FIG. 1A shows a standard vertical configuration of the fluoroscopic system **100** where the x-ray source is directed upward to the detector. As can be seen, a worker **105** primarily has exposure in the C region, with their head even farther away. FIG. 1B shows the radiation exposure of the worker **105** when the system **100** is at 30° from vertical. Here, the worker **105** primarily has exposure in the B region with some exposure in the A region. FIG. 1C shows the

radiation exposure of the worker **105** when the system is in the horizontal position. Here, the worker **105** is outside the illustrated iso-exposure fields. FIG. 1D shows a system in an inverse vertical configuration where the x-ray source is directed downward to the detector in a manner that is not recommended. As can be seen, such a configuration for the system **100** results in the worker **105** with their head in the B region. These images demonstrate that a worker's radiation exposure can vary significantly depending on the orientation of the equipment and the occupational worker's stance about the field. (Figure based on G Sackett. 2020. Radiation Safety Issues for Radiologic Technologists. Presentation by Integrated Science Support, Inc.)

[0035] FIG. 2 is an example application of an SRSRS article as disclosed herein, used in a fluoroscopy suite. As illustrated in the image of FIG. 2, a fluoroscopy system **200** in the configuration illustrated in FIG. 1A may be causing excess radiation exposure to the workers. By wearing an SRSRS article, localized exposure can be indicated in real-time. In real time, the article detects the locus of intense radiation on various locations, such as on the wearer's body and reports the location with, for example, LED signals that are easily visible by those in the vicinity of the article. The stars superimposed on the protective clothing of the clinicians represent real-time illuminating LEDs, which are embedded into the aprons of the practitioners. Here, low rate detection (**L**), medium rate detection (**M**), and high rate detection (**H**) are indicated (and may also be distinguishable by the amount/intensity of light emitted and/or the color). The colors of the LEDs can be configured to reflect detected radiation levels at the corresponding physical locations, e.g., low levels of radiation are illuminated with green LEDs, medium rates are orange LEDs, and high detection rates are illuminated with red LEDs. The reporter LEDs are disposed on the outside of the lead shielded gowns worn by the workers, such that any illuminated LEDs are easily visible.

[0036] FIGs. 3A and 3B show a perspective view and representative schematic, respectively, of an example article providing a localized radiation sensing and reporting surface. Referring to FIG. 3A, an article **300** is provided that includes a substrate **310**, a plurality of radiation sensors **315**, and alert circuitry **320** coupled to the plurality of radiation sensors **315**. The substrate **310** can be formed of a flexible material, and may be in the form of a garment, cloth (e.g., which can be draped on equipment, people, or even the floor), or floor covering (e.g., intended for covering floor surfaces and possible walking). In the illustrated example, there are three radiation sensors **315A**, **315B**, **315C** and each of these radiation sensors are disposed at a corresponding position (e.g., A, B, and C) on the substrate **310**. It should be understood that although the sensors

are described as being “on” the substrate, this refers to any position with respect to the substrate, including being within, under, or above the substrate and that it is intended to indicate that the substrate holds the sensors. In some cases, the radiation sensors include scintillators and scintillator detectors (i.e., devices that detect scintillation of the scintillators, such as photodetectors that detect the light signal from a scintillator). In some cases, the radiation sensors include solid state device radiation detectors (e.g., semiconductor-based devices). Scintillator-based radiation sensors are described in detail with respect to FIGs. 4, 6, 7A, 7B, 9A, 9B, 11A, and 11B. Example substrates incorporating such scintillator-based radiation sensors are described in detail with respect to FIGs. 8A-8C, 10A-10C, and 12A-12C.

[0037] The alert circuitry indicates, in real time, a localized detection of radiation according to corresponding one or more positions (e.g., A, B, and C) on the substrate **310** of a particular one or more radiation sensors of the plurality of radiation sensors **315**. In some cases, the alert circuitry includes one or more LEDs. In some cases, the alert circuitry includes a speaker and sound generator. In some cases, multiple types of alerts are provided (e.g., two or more of local light, local sound, local haptic, remote light, remote sound, and remote haptic). In the illustrated example, each sensor (**315A**, **315B**, **315C**) has a corresponding alert circuitry output **320A**, **320B**, **320C**. For example, as shown in the representative schematic of FIG. 3B, each sensor is coupled to a corresponding alert circuitry. In some cases, the corresponding alert circuitry is a light source such as an LED (such that the alert circuitry **320** includes a plurality of LEDs, and each LED of the plurality of LEDs provides the alert circuitry outputs **320A**, **320B**, **320C**). For example, each LED is coupled to a corresponding one radiation sensor of the plurality of radiation sensors and located within a region of the corresponding position of the radiation sensor on the substrate (such as shown in FIG. 3A). The LEDs may be any suitable light emitter (including inorganic and organic LEDs), as well as single and multicolor LEDs from ultraviolet to infrared wavelengths. Indeed, any available compact low power light source may be used.

[0038] Also illustrated in FIG. 3B is readout circuitry **330**, which may be included when the alert circuitry involves more involved readout processing (e.g., where more than one sensor is coupled to a particular alert circuitry output and it is desired to identify which location detected the radiation) and/or is communicated to an external system (e.g., via optional transmitter **340**). Readout circuitry can include detectors, selectors to address specific sensors, comparators, and/or

other suitable devices. Through the optional transmitter **340**, remote logging of the detected radiation exposure is also possible.

[0039] FIG. 4 is a schematic representation of a radiation detection system according to one aspect of the present disclosure. In this example embodiment, a 4-pixel section is shown, where each of the broken-line squares (labeled **402-1**, **402-2**, **402-3**, **402-4**) represent a unit surface area of a garment or sheet formed, for example, with scintillators (see e.g., FIGs 8B and 10B).

[0040] A lateral view of the weave from **A1** is shown as **A1L** and a lateral view of the weave from **C1** is shown as **C1L**. The surface areas **402-1**, **402-2**, **402-3**, **402-4** are defined by a region corresponding to reporter LED(s) **404-1**, **404-2**, **404-3**, **404-4**. In a non-limiting example, each unit area is equal to or greater than 5 cm² and can be formed of one or more crossed-fibers (e.g., unit area of 1 x 1 strands, 1 x 2 strands, 2 x 2 strands, 2 x 4 strands, 3 x 3 strands, 5 x 5 strands, 6 x 6 strands, etc.), but is in general limited in size in order to provide location-specific information. In the context of the present disclosure, these unit areas and/or the reporter LEDs can be referred to as "pixels". Additionally, the term "LED" can refer to a single LED or an array of LEDs (e.g., RGB) that can be addressed together to produce any color in the available range, and thus include visible, infrared, and/or ultraviolet (UV) emitting LED(s). Different sized pixels can contain different numbers of LEDs in a regional distribution.

[0041] The example embodiment of FIG. 4 uses scintillators in the form of scintillating optical fibers (SOFs). SOFs consist of a core scintillating material that produces light from radiation interactions and are largely transparent to that light. The multi-mode optical fibers transmit the generated light through total internal reflections to a remote detector. The fibers are woven together in a generally orthogonal manner to create a mesh. It should be understood that the number of fibers shown in FIG. 4 are for illustration only and should not be construed as limiting the number of fibers in the arrangement. Various types of SOF fibers are suitable for the disclosed article. Additionally, various weave patterns can be used without departing from the scope of the disclosure. Example weave patterns include layered, plain, stranded, and twill, among others (see also FIGs. 14A-14D), ensuring good signal conductance with minimal bending that can otherwise compromise signal level. Layered fibers could be held together by physical connector means like a brace or tie, or by bonding agent, or by coating that mutually covers the layers of fibers. For example, fibers can be coated by dipping or spraying an opaque flexible coating to cover the layers of fibers. The mesh layer and the LED layer can be coupled together or integrated

into single substrate. For example, the mesh layer could be used as the substrate to support the LED layer. Furthermore, in some integrated implementations, electronics could be weaved in since they are mostly opaque and not substantially attenuating for the ionizing radiations.

[0042] The types of SOF fibers suitable for the disclosed article include fibers with different cross-sections (e.g., square or circular) and a range of diameters (e.g., Kuraray Corp. SCSF-78 in 0.1, 0.25 and 0.5mm ϕ). The types of fibers can also include combinations of SOFs and optical fibers, in bundles or fused along the linear length of signal travel, which do not scintillate but still carry signals from the SOFs.

[0043] FIG. 5 shows an example of various fiber configurations of equivalent detection volumes. Referring to FIG. 5, various diameters of fibers can be used. In some cases, the fibers can be provided in a bundle. A bundle of small diameter SOFs can be held together like fibers in garment material. The individual fibers can be bundled together in a parallel fashion, or the fibers can be twisted together, similar to yarn, and in some embodiments the fibers can be combined with non-scintillating fibers or metal strands or wires for additional strength. Other characteristics of the system can also be customized, such as fill factor (spacing of apertures between fibers), overall packing, and flexibility.

[0044] Returning to FIG. 4, fiber groups associated with a row or column of pixels extend to a perimeter of the system, and they are connected to detector channels A, B, C, and D. In this example, each channel is associated with one row or column of pixels (see also FIG. 7A).

[0045] FIG. 6 shows an example of a portion of a detector configuration. Referring to FIG. 6, a unit area **600** of a SOF mesh formed by strands **602** and corresponding LED **605** is shown with one photodetector for each axis (x-axis photodetector **610** and y-axis photodetector **620**), which can correspond, for example, to detector channel B and D of FIG. 4. The photodetectors **610**, **620** can be coupled to processing electronics **630**. When a group of SOFs (e.g., within defined unit area region **600** associated with LED **605**) are illuminated by the presence of radiation, the optical signals travel through the fibers and are registered by the detector(s) **610**, **620**. The detector(s) **610**, **620** are in turn connected to the overlaid LED layer (e.g., LED **605**). In some cases, the detectors are coupled to circuitry that cause the LED to be connected to a power source to turn on. In some cases, a prescribed program can be used to instruct the LED associated with the illuminated pixel area to turn on.

[0046] FIGs. 7A and 7B illustrate configurations for a radiation detection system using a scintillation optical fiber mesh coupled to photosensors in one and two directions. Referring to FIG. 7A, similar to the embodiment shown in FIG. 4, one photodetector may be provided for each axis and one LED can be disposed at the center of a region-of-interaction location. Referring to FIG. 7B, a radiation detection system can involve two photodetectors for each axis. Having two photodetectors for each axis can allow additional capabilities, such as measuring relative illumination strength to determine the XY location of the defined unit area exposed to radiation. In the crossed-fiber/weaved configurations where the SOFs are multiplexed, an XY determination is made to identify the pixel that detects radiation in order to reduce the number of photodetectors. For example, there can be $2 \times N$ photodetectors for a square grid.

[0047] In some embodiments, the detector is in the form of one or more portable silicon photomultipliers (SiPMs) or other suitable, low power, compact photo-sensitive device. In some embodiments, SiPMs are disposed along the edge of the system and are associated with a lengthwise dimension of the system. Thus, the SiPMs establish a “grid” or coordinate plane of the surface, which is translated into discrete XY locations for reporting. One method by which a radiated pixel can be identified is through the simultaneous illumination of crossing strands. For example, in the embodiment shown in FIG. 4, channels AC, AD, BC, and/or BD may be detected. The LEDs are independently addressable after XY determination from the coincidence circuitry, and the color band can be controlled according to prescribed ranges of exposure or rates of detection. These steps can be accomplished through a control system (and suitable circuitry and/or software programming executed by hardware processor/circuitry).

[0048] FIGs. 8A-8C illustrate example article substrate configurations with scintillation optical fiber mesh. Referring to FIGs. 8A and 8B, an article can be formed of multiple layers. Here, an article can include first (transparent) fabric layer **802** over a substrate layer **804** with LED **805**, which is on a converter/graded absorber layer **806**, which is on a SOF mesh layer **808**, which is above one or more radiation absorptive shields (e.g., double Pb Shield 1-1 **810** and Pb Shield 1-2 **812**). The article further includes a backing of a second fabric layer **814** at the back side of the double lead shield. This configuration is suitable for a garment (and more or fewer radiation absorptive shields may be included, depending on desired stopping power, material flexibility, and weight). For use as a drop cloth, protecting workers from radiation from the floor (e.g., due to a spill), the article layers can be, from top (e.g., exposed to room) to bottom (e.g., facing floor): a

second (sufficiently transparent) fabric layer **814**, substrate layer **804** with LED **805**, one or more radiation absorptive shields (e.g., double Pb Shield 1-1 **810** and Pb Shield 1-2 **812**), SOF mesh layer **808**, converter/graded absorber **816** and first fabric layer **802**. The converter/graded absorber **816** may be a same material and thickness or a different material and/or thickness as compared to the converter/graded absorber **806**. For example, converter/graded absorber **806** may be thinner than the converter/graded absorber **816** where the LED substrate layer **804** provides some converter/absorber functionality. The one or more radiation absorptive shields can be formed of any suitable material, depending on the type of radiation intending to absorb, for example, plastic, lead, or a combination of plastic and lead may be used. As an illustrative example, x-ray or gamma-ray absorption can be facilitated by Pb Shield layers in the form of the malleable lead layers used in a standard occupational gown.

[0049] FIGs. 9A and 9B illustrate a detector configuration where a single scintillator and the detector are integrated and disposed directly in the unit area. Referring to FIG. 9A, a unit area **900** formed of an individual region composite (“composite detector”) is shown having an LED **910**, a scintillation detector **920**, photodetector **930**, and output to processing electronics **940**. Such a configuration of scintillation detector **920** and photodetector **930** may be considered a scintillator-light pipe configuration. Referring to FIG. 9B, similar to described above, the unit area LEDs can be independently addressable from individual pixel determination (e.g., as A1, A2, B1, and B2 in FIG. 9B).

[0050] FIGs. 10A-10C illustrate example article substrate configurations with individual region composites. Referring to FIGs. 10A and 10B, an article can be formed of multiple layers, including, from top to bottom: a first (transparent) fabric layer **1002**, substrate layer **1004** with LED **1005**, converter/graded absorber **1006**, composite detector **1008** (e.g., formed of a scintillator, light guide/scintillator, and photodetector), one or more radiation absorptive shields (e.g., double Pb Shield 1-1 **1010** and Pb Shield 1-2 **1012**), and second fabric layer **1014**. For use as a drop cloth, protecting workers from radiation from the floor (e.g., due to a spill), the article layers can be, from top (e.g., exposed to room) to bottom (e.g., facing floor): a second (sufficiently transparent) fabric layer **1014**, substrate layer **1004** with LED **1005**, one or more radiation absorptive shields (e.g., double Pb Shield 1-1 **1010** and Pb Shield 1-2 **1012**), composite detector **1008**, converter/graded absorber **1016**, and first fabric layer **1002**. The converter/graded absorber **1016** may be a same material and thickness or a different material and/or thickness as compared to the

converter/graded absorber **1006**. For example, converter/graded absorber **1006** may be thinner than the converter/graded absorber **1016** where the LED substrate layer **1004** provides some converter/absorber functionality. The one or more radiation absorptive shields can be formed of any suitable material, depending on the type of radiation intending to absorb, for example, plastic, lead, or a combination of plastic and lead may be used.

[0051] One reason for having multiple thinner layers and small segments of detector area is so that the layered composite device is flexible and can mold onto several smoothly varying surfaces that it is in contact with. Other non- or weakly-attenuating layers can be included for protection against (corrosive) fluids or even gases by hermetically sealing/encapsulating the detector, LED, and any electronics layers.

[0052] In some cases, the individual region composite configurations can include more photodetectors than that used for the SOF implementations.

[0053] FIGs. 11A and 11B illustrate a detector configuration where the scintillator, detector, and LED are integrated and disposed directly in the unit area. Referring to FIG. 11A, a unit area **1100** formed of an integrated element is shown having a scintillation detector/LED **1110** (with LED light shown emitted as **1120**). Here, any available low-profile, light-weight detector (detector/reporter device) may be used. For example, materials such as perovskite crystals can act as both detector and bright LED-like emitter. Referring to FIG. 9B, similar to described above, the unit area LEDs can be independently addressable from individual pixel determination (e.g., as A1, A2, B1, and B2 in FIG. 11B).

[0054] FIGs. 12A-12C illustrate example article substrate configurations with integrated elements. Referring to FIGs. 12A and 12B, an article can be formed of multiple layers, including, from top to bottom: a first (transparent) fabric layer **1202**, converter/graded absorber allowing light to pass through it **1206**, integrated element **1208** (e.g., integrated detector/reporter) providing emitted light **1209** when reporting detection, one or more absorptive shields (e.g., Pb Shield 1-1 **1210** and Pb Shield 1-2 **1212**), and second fabric layer **1214**. For use as a drop cloth, the article layers can be, from top (e.g., exposed to room) to bottom (e.g., facing floor): a first fabric layer **1202**, a first converter/graded absorber allowing light to pass through it **1206-1**, integrated element **1208** (e.g., integrated detector/reporter) providing emitted light **1209** when reporting detection, a second converter/graded absorber **1206-2**, and second fabric layer **1214**. The one or more radiation absorptive shields can be formed of any suitable material, depending on the type of radiation

intending to absorb, for example, plastic, lead, or a combination of plastic and lead may be used. The first converter/graded absorber **1206-1** and the second converter/graded absorber **1206-2** can be the same or different materials and/or thicknesses. In some cases, the second converter/graded absorber **1206-2** can be of a same material and thickness as converter/graded absorber **1016** of FIG. 10C.

[0055] As illustrated above, an SRSRS system can include a variety of layers in addition to the sensor/detector and LED layers. These can be, for example, shielding layers, radiation conversion layers, waterproof layers, fabric layers, and/or any other suitable types of layers.

[0056] FIG. 13 is an example schematic of a layered SRSRS configuration showing various radiation interactions in different layers of the SRSRS. For simplicity, the LED layer is not shown. In this example embodiment, the additional layers include fabric (Fab) **1302** and **1304**, an optional converter (Cnvt) or Graded Absorber (GA) (Cnvt/GA **1306**), a SOF XY-mesh **1308**, and an absorptive shield layer. In this example, two absorptive shield layers of Pb shield 1 **1310** and Pb shield 2 **1312** are shown with x-ray or gamma-ray photons impinging on the upper incident surface. The impinging ionizing rays are labelled A-F and depict possible operational functionalities. Ray (A) is a fully absorbed photon in Cnvt/GA **1306** and produces no signal in SOF mesh **1308**. Rays (B) are photons which produce secondary electrons (e^-) or scattered photons (γ') upon interacting in the Cnvt/GA **1306** and can “shower” the SOFs **1308**. Rays (C) are fully absorbed photons in the SOFs that produce detectable optical signals as well as secondary electrons, as do rays (D) scattered photons, which may expel electrons. Photons that do not interact in the source-side layers can still interact in the protective shields **1310**, **1312** and generate e^- electrons or (F) characteristic x- rays (x_k) which may backscatter to the SOFs **1308** and produce signals. Hence, it is to be understood that any combination of the foregoing direct or indirect types of events, as well as other types that will be evident to those of skill in the art, can be detected and reported by the SRSRS system.

[0057] In some embodiments, the SRSRS system also includes a haptic layer (not shown). The haptic layer can be located on a layer opposite the LED layer (e.g., on a side close to the wearer's body). The haptic layer can be used either in addition to the LED reporters or as an alternate reporting method to inform the wearer of the exposure.

[0058] The SRSRS also includes a control system for processing, transferring, analyzing, recording, and/or reporting radiation. In addition to location-specific reporting, exposure

information can also be relayed or reported in any other suitable manner, such as wirelessly to a user interface and/or displayed other ways, stored on computer-readable media for retrospective analysis, etc.

[0059] Another aspect of the present disclosure provides a method of detecting radiation exposure with the disclosed devices and systems.

[0060] Another aspect of the present disclosure provides all that is described and illustrated herein.

[0061] The following Examples are provided by way of illustration and not by way of limitation.

[0062] **Prototype Development**

[0063] Mesh configurations

[0064] Flexibility, strength, and sensitivity are important characteristics for the SOF detection layer. FIGs. 14A-14D illustrate example classical fiber weaves that can be used for a SOF mesh. In addition to the various weaves, different SOF cross-sections (square and circular) and diameters (e.g., Kuraray Corp. SCSF-78 in 0.1, 0.25 and 0.5mm diameter or cross-section) may be used.

[0065] For the prototypes, the SOF core is made of polystyrene ($\rho = 1.05\text{g/cm}^3$), and x-ray tubes in fluoroscopy are normally operated at 80kVp, with a mean energy of 50keV. Thus, if a solid 0.2mm thick polystyrene plastic plane (representing a bi-layered woven mesh of the 0.1mm fibers) is considered, the NIST-XCOM absorptions are 0.42% and 0.36% at 50 and 80keV, respectively. Considering a 1mm thick polystyrene plastic plane (representing a bilayer of 0.5mm SOFs), the absorptions are 2.1% and 1.8% at the given energies, respectively. Since a mesh of fibers will have even less sensitivity than a solid plane, it is possible to increase sensitivity by bundling small SOFs by volume in the mesh. Size-dependent durability in the field can determine what SOF size and bundle size and mesh type would be most suitable for a given application. Operating conditions in the battlefield or at a nuclear reactor differ substantially from those in the medical fluoroscopy suite, which can necessitate different combinations optimized under different conditions.

[0066] Characterization of light output

[0067] FIGs. 15A and 15B illustrate light intensity characterizations. FIG. 15A depicts DETECT optical simulation results illustrating the mean number of reflections with various fiber

diameters for a fixed numerical aperture (NA) = 0.75. Note the asymptotic number of reflections with increasing distance from the detector. FIG. 15B shows a comparison of measured and DETECT simulated signal transmission in a 2mm ϕ multi-mode optical fiber with different polishes on the cladding. With layered SOFs and flexing of the meshes, one might expect normal wear-and-tear (unless other protective material/sleeve is also present on the outside of the fiber) yielding a “ground clad” surface on the fibers.

[0068] In clear optical and SOFs, photons with incident angles greater than or equal to the critical angle (derived from Snell’s law as $\theta_{\text{crit}} = \sin^{-1}(n_{\text{clad}}/n_{\text{core}})$) propagate losslessly within the optical fiber due to total internal reflection. This is true when the fiber is straight, though the number of reflections varies with fiber diameter and length, as shown in FIG. 15A. When a fiber is curved, as expected in woven patterns, and when the entire woven sheet is wrapped or contorted around an object or other surface, more light escapes. The losses in fiber transmission due to the length of the optical fiber depend on several factors: numerical aperture, radius of curvature of the bend, and the number of loops or bends. An approximate parameterization for the loss L from a fiber bent in N loops in a fixed radius r is given as: $L = k \cdot \sqrt{N}/r^c$ where k and c are constants derived from fit parameters to measured data. Fortunately, the measured losses from various optical fibers are usually small ($\leq 3\%$) for a single loop with radii down to 2cm, which is a tight loop. Even for 15 loops with 2cm radius, the losses total about 5%.

[0069] Optimum coupling between scintillators and detectors

[0070] FIG. 16A shows a photograph of variously grouped fiber optic bundles of different fiber sizes (Cartesian grids at left & middle and hexagonal close packed array at right) in a flange which can be coupled to a detector. Fiber sizes shown are different sizes for a different application. US penny is included for scale. FIG. 16B shows various commercially available SiPM arrays and front-end electronics.

[0071] Various strategies for securing and coupling the SOFs to the SiPM detectors, similar to those implementations shown in FIGs. 16A and 16B, include grouping strands of SOFs in square grids, or stacking in hexagonal close packing configurations, or pseudo-random bundling of many fibers. For example, while each square bundle in FIG. 16A would be miniaturized to cover the individual larger (e.g., $3 \times 3 \text{ mm}^2$) SiPM elements (FIG. 16B) on 3.36mm pixel pitch, and support the considerably smaller SOFs, arrays of such bundles are used for the 8x8 array of SiPM elements. Coupling could utilize all manner of colored materials, e.g., black, grey, and white

plastic supports for the fiber bundles and arrays of bundles based on securing the fibers and desire to minimize any optical crosstalk between SiPM pixels, and determine the maximum pulse heights for known irradiation sources. Linear arrays of SiPMs and individual SiPMs or other compact, lightweight, low power optical light photon detectors can be used.

[0072] Coincidence projection methodology

[0073] Silicon photomultipliers (SiPM) improve over vacuum PMTs including low-light sensitivity and fast coincidence detection, and their form factor allows placing SiPM arrays in compact applications and configurations. Using a modified and versatile *PETsys TOF ASIC Evaluation Kit* and two 8x8 arrays (e.g., *KETEK* 8x8 PA3325-WB-0808 SiPM array having 3x3 mm² pixels (see FIG. 16B), 45% QE_{peak} at 450nm, low dark count noise, 230psec coincidence timing resolution), the SiPM arrays are adapted for coincidence detection of the X and Y bundles of SOFs.

[0074] Given that x-ray scatter fields have maximally 500mR/h exposure rates, x-ray fluoro fluence rates of 4.3x10⁴ph/mm²-sec are calculated. Also given a calculated detection sensitivity of ~2% for the SOFs, this indicates that the SRSRS device could be exposed to fluxes of 8.6x10⁴ph/cm²-sec over the nominally defined 5cm² sensitive and LED-pixelated region, well within the *PETsys e-Kit*'s GHz event processing capability. For the nuclear application in detecting small sources, the dynamic range of the SRSRS can be wide ranging, similar to a dose calibrator, since a 1-microCurie source yields ~3.7x10⁴ph/micro-Ci, half of which may be directed towards the device. A milli-Ci radiation source has 3.7x10⁷ph/milli-Ci, and whose detected count rate is still well within the capabilities of the *PETsys e-Kit* processing bandwidth capability, and so on.

[0075] Instead of the usual coincidences such as arising from a positron-electron annihilation event and measured in PET imaging, "projection coincidences" can be established between the X and Y directional SOFs in a mesh coupled to the SiPM array elements. This means that the X and Y gridded SOFs will detect independent photons occurring in clusters or bunches from the fluoro tube within a small time window; it is the near-simultaneous detection in each X and Y SOF that establishes the location of the interaction for any given "event" to be registered. Using the versatile *PETsys e-Kit*, it is possible to vary the coincidence timing acceptance windows from 230psec to 10's of nsec for different collimated flux rates when irradiating different regions of the SRSRS. With different electronics capabilities, yet further ranges of acceptance windows would be possible. It is possible to implement the best lower-level-discriminator (LLD) threshold

set for noise and energy discrimination, and it is not intended to window on any specific energy due to the broadband nature of fluoro x-ray spectra, and especially the spectrally non-uniform scatter distributions.

[0076] Low-profile LEDs and grid circuitry

[0077] As an example, it is possible to configure commercially available, programmable arrays of LEDs (on $\sim 8 \times 32 \text{ cm}^2$ sheets) to particular specifications, using one LED per 5 cm (and up to 25 cm² or larger, depending on the available material). FIG. 17 illustrates a representative flexible LED panel for testing. For the prototype, the LED panel is *WS2812 IC Individually Addressable DC5V IP30 Zofipo Pixels LED* light sheet. Each LED on the sheet is addressable through programmable *Arduino* boards. The LED panel can be tested alone, and then integrated anterior to the SOF detector panel such that the LED “pixel” physically corresponds to the appropriate XY-SOF mesh region. The results of the XY-projection coordinate information will identify the appropriate pixel (XY region) where there was a radiation interaction, and that location information will address the LED panel, such as by using an *Arduino Zero* (or *Arduino IC Digital Addressable Dream Color RGB*) programmable board. Depending on the event rate detected by the *PETsys* unit, the LEDs can be enabled to produce an exposure-dependent color: red for high rate (e.g., 100-500mR/hr), orange for medium (50-100mR/hr), and green for low (1-50mR/hr; other colors and ranges are possible). There may also be a range setting to distinguish rates in fluoroscopy compared with nuclear medicine spilled sources, which have considerably different fluxes depending on the amount of radioactivity, though also more proximal contact which affects overall efficiency of detection.

[0078] Alternately, the existing flexible LED panel can be used by only addressing a sparse array of LEDs on the panel at a selected detection area (anywhere from 5cm² and up). LED lighting due to radiation interactions in the diodes themselves may be an issue in anticipated high radiation fields and could be used like radiation detectors (e.g., FIGs 10A – 10C). It is possible to determine electronic lower-level discriminator (LLD) and source strength thresholds. One remedy is to truly ensure a sparse LED array, rather than only sparsely utilizing elements on the higher density array that can be purchased commercially or designed specifically for these applications. If the purchased surfaces do not flex as readily as the SOF meshes, the LED arrays will be reconfigured into loosely bound, but secured, strips instead of leaving them in sheets. This way the strips of

LEDs will still be addressable in an identical way as on the prefab sheets, but be more highly flexible.

[0079] The radiation detection systems described herein optionally include control systems for operational aspects of the systems (e.g., signal analysis, LED illumination instructions, user interface, display of results, etc.). The control systems can be implemented in hardware, software, firmware, or combinations of hardware, software and/or firmware. In some examples, the control systems described in this specification may be implemented using a non-transitory computer readable medium storing computer executable instructions that when executed by one or more processors of a computer cause the computer to perform operations. Computer readable media suitable for implementing the control systems described in this specification include non-transitory computer-readable media, such as disk memory devices, chip memory devices, programmable logic devices, random access memory (RAM), read only memory (ROM), optical read/write memory, cache memory, magnetic read/write memory, flash memory, and application-specific integrated circuits. In addition, a computer readable medium that implements a control system described in this specification may be located on a single device or computing platform or may be distributed across multiple devices or computing platforms.

[0080] Articles "a" and "an" are used herein to refer to one or to more than one (i.e., at least one) of the grammatical object of the article. By way of example, "an element" means at least one element and can include more than one element.

[0081] "About" is used to provide flexibility to a numerical range endpoint by providing that a given value may be "slightly above" or "slightly below" the endpoint without affecting the desired result.

[0082] The use herein of the terms "including," "comprising," or "having," and variations thereof, is meant to encompass the elements listed thereafter and equivalents thereof as well as additional elements. As used herein, "and/or" refers to and encompasses any and all possible combinations of one or more of the associated listed items, as well as the lack of combinations where interpreted in the alternative ("or").

[0083] As used herein, the transitional phrase "consisting essentially of" (and grammatical variants) is to be interpreted as encompassing the recited materials or steps "and those that do not materially affect the basic and novel characteristic(s)" of the claimed invention. Thus, the term "consisting essentially of" as used herein should not be interpreted as equivalent to "comprising."

[0084] Moreover, the present disclosure also contemplates that in some embodiments, any feature or combination of features set forth herein can be excluded or omitted. To illustrate, if the specification states that a complex comprises components A, B and C, it is specifically intended that any of A, B or C, or a combination thereof, can be omitted and disclaimed singularly or in any combination.

[0085] Unless otherwise defined, all technical terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs.

[0086] No admission is made that any reference, including any non-patent or patent document cited in this specification, constitutes prior art. In particular, it will be understood that, unless otherwise stated, reference to any document herein does not constitute an admission that any of these documents forms part of the common general knowledge in the art in the United States or in any other country. Any discussion of the references states what their authors assert, and the applicant reserves the right to challenge the accuracy and pertinence of any of the documents cited herein. All references cited herein are fully incorporated by reference, unless explicitly indicated otherwise. The present disclosure shall control in the event there are any disparities between any definitions and/or description found in the cited references.

[0087] Although the subject matter has been described in language specific to structural features and/or acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above. Rather, the specific features and acts described above are disclosed as examples of implementing the claims and other equivalent features and acts are intended to be within the scope of the claims.