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(54) Title: OPTICAL FIBER BASED SENSING FOR SMART ELECTRICAL CABLES AND DISTRIBUTED RADIATION DETECTION

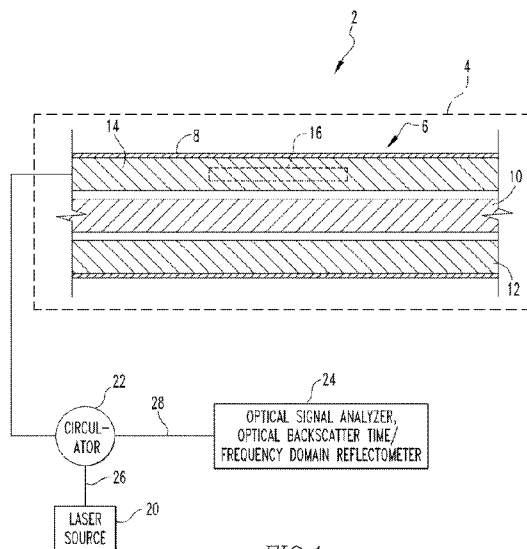


FIG.1

(57) Abstract: A cable device includes a sheath member, a number of electrical cables provided within the sheath member, and an optical fiber sensing member provided within the sheath member. The optical fiber sensing member includes a functionalized optical fiber based sensor device structured to exhibit a change in one or more optical properties in response to changes in a parameter of interest. Also, a method of sensing radiation includes introducing a source light into an optical fiber sensing member provided within a structure, wherein the optical fiber sensing member comprises a functionalized optical fiber based sensor device structured to exhibit a change in one or more optical properties in response to radiation, detecting sensing light generated in response to the source light, and determining a radiation level at a plurality of locations within the structure using the detected sensing light and a distributed sensing scheme.



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OPTICAL FIBER BASED SENSING FOR SMART
ELECTRICAL CABLES AND DISTRIBUTED RADIATION
DETECTION

CROSS-REFERENCE TO RELATED APPLICATIONS

- [01] This application claims priority under 35 U.S.C. § 119(e) from U.S. provisional patent application no. 62/312,059, entitled “Smart Electrical Cable Enabled by Optical Fibers” and filed on March 23, 2016, the contents of which are incorporated herein by reference.

GOVERNMENT CONTRACT

- [02] This invention was made with government support under grant # DE-NE0008303 awarded by the Department of Energy (DOE). The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

- [03] The disclosed concept pertains to optical fiber based sensors used in industrial, commercial or residential structures, such as, without limitation, a nuclear reactor, and in particular, to a smart electrical cable that is structured to sense one or more parameters using optical fiber sensing technology and to a system and method for distributed radiation sensing.

2. Description of the Related Art

- [04] The safe and efficient operation of industrial facilities, such as nuclear reactors and various fuel cycle processes, can be significantly enhanced through information gathered by ubiquitous sensor technology. The deployment of advanced sensors is important to safe-guard such facilities, like nuclear energy systems, at both component and system levels. For sensor networks used in nuclear energy systems, they must withstand harsh environments and perform proper measurements during both normal operation and in harsh post-accident situations for long periods of times. At the same time, the deployment of the sensor network should not significantly

increase engineering complexities and cost for new and existing nuclear power systems, which are already very expensive.

SUMMARY OF THE INVENTION

- [05] In one embodiment, a cable device is provided that includes a sheath member, a number of electrical cables provided within the sheath member, and an optical fiber sensing member provided within the sheath member. The optical fiber sensing member includes a functionalized optical fiber based sensor device structured to exhibit a change in one or more optical properties in response to changes in a parameter of interest.
- [06] Other embodiments include a system and a method that employ a cable device as just described.
- [07] In still another embodiment, a method of sensing radiation within a structure is provided that includes introducing a source light into an optical fiber sensing member provided within the structure, wherein the optical fiber sensing member comprises a functionalized optical fiber based sensor device structured to exhibit a change in one or more optical properties in response to radiation, detecting sensing light generated in response to the source light, and determining a radiation level at a plurality of locations within the structure and along the optical fiber sensing member using the detected sensing light and a distributed sensing scheme. A system that employs this method is also provided.

BRIEF DESCRIPTION OF THE DRAWINGS

- [08] FIG. 1 is a schematic diagram of a sensing system according to an exemplary embodiment of the disclosed concept;
- [09] FIG. 2 is a schematic diagram of a sensing system according to an alternative exemplary embodiment of the disclosed concept; and
- [10] FIG. 3 is a schematic diagram of a sensing system according to a further alternative exemplary embodiment of the disclosed concept.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

- [11] As used herein, the singular form of “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise. As used herein, the statement that two or more parts or components are “coupled” shall mean that the parts are

joined or operate together either directly or indirectly, i.e., through one or more intermediate parts or components, so long as a link occurs.

- [12] As used herein, “directly coupled” means that two elements are directly in contact with each other.
- [13] As used herein, “fixedly coupled” or “fixed” means that two components are coupled so as to move as one while maintaining a constant orientation relative to each other.
- [14] As used herein, the word “unitary” means a component is created as a single piece or unit. That is, a component that includes pieces that are created separately and then coupled together as a unit is not a “unitary” component or body.
- [15] As used herein, the statement that two or more parts or components “engage” one another shall mean that the parts exert a force against one another either directly or through one or more intermediate parts or components.
- [16] As used herein, the term “number” shall mean one or an integer greater than one (i.e., a plurality).
- [17] As used herein, the term “functionalized optical fiber based sensor device” shall mean a device that includes an optical fiber having one or more sensor elements (including transient sensor elements) such that the functionalized optical fiber based sensor device exhibits a change or changes in optical properties (such as transmitted spectrum, intensity, or polarization, without limitation) in response to changes in environmental parameters in the environment around the in-fiber sensor element(s) (such as, without limitation, radiation, chemical composition, strain and/or temperature).
- [18] As used herein, the term “high-temperature” shall mean temperature of approximately 400°C and higher.
- [19] As used herein, the term “high-temperature stable fiber Bragg grating” shall mean a fiber Bragg grating capable of maintaining its reflective properties at high-temperatures for long periods of time (e.g., weeks, months or years of continuous operation) without significant degradation of those properties.
- [20] As used herein, the terms “scattering based system” and “scattering based interrogation approach” shall mean a system or interrogation method in which the basis of measurement is the collection of light scattered by materials present in the fiber sensor or the environment, respectively.

- [21] As used herein, the term “back scattering based interrogation” shall mean sensor interrogation utilizing scattering emerging from the same end of the sensing fiber as the interrogation source.
- [22] Directional phrases used herein, such as, for example and without limitation, top, bottom, left, right, upper, lower, front, back, and derivatives thereof, relate to the orientation of the elements shown in the drawings and are not limiting upon the claims unless expressly recited therein.
- [23] The disclosed concept will now be described, for purposes of explanation, in connection with numerous specific details in order to provide a thorough understanding of the subject invention. It will be evident, however, that the disclosed concept can be practiced without these specific details without departing from the spirit and scope of this innovation.
- [24] The disclosed concept, in one embodiment, uses electrical cables, which are ubiquitously deployed in industrial, commercial, and residential buildings, as sensor platforms. Specialty optical fibers are seamlessly integrated into electrical cables as sensing devices. In one aspect, the disclosed concept uses distributed fiber-sensing schemes such as, but not limited to, Rayleigh backscattering optical frequency domain reflectometry (R-OFDR), Brillouin backscattering optical time domain reflectometry (BOTDR), Raman backscattering, and fiber Bragg grating array (FBG) sensing, to detect both physical parameters (e.g., radiation, temperature, strain, pressure, liquid levels) and chemical information (e.g., radical chemical species (such as hydrogen) concentrations) with high spatial resolutions (1 mm to 1 meter). Alternatively, as described herein, the disclosed concept may also use single point sensing to sense such parameters.
- [25] Since electrical cables are already part of industrial (e.g., nuclear power), commercial, and residential structures (e.g., buildings), no alteration or modification of such structures is needed to accommodate new sensors. This will greatly reduce costs and engineering barriers for sensor deployments. The disclosed concept thus provides a feasible and cost-efficient solution for building smart infrastructures and cyber physical systems. The disclosed concept allows for: (i) seamless integration of optical fiber with electric cables as sensors, (ii) a distributed fiber optical sensing scheme for measurement across large distance with spans from 100 meters to up to 100 km with high spatial resolutions, and (iii) fiber

functionalization for multi-parameter measurements for temperature, strain, pressure, radiation, flow, chemical species, etc.

[26] As noted above, the disclosed concept may employ single point fiber-optic based sensing techniques to sense various parameters. While effective, such schemes are only capable of providing information about the average value of the sensed parameter at the location of the in-fiber sensing element. Thus, according to a further aspect of the disclosed concept, optical fiber sensor technology is integrated with more complex interrogation approaches (as described below) to enable distributed sensing of parameters of interest (such as radiation, chemical composition, temperature or strain distribution) across a location. Multi-point sensing can be done in a variety of ways which may resolve a continuous distribution of the sensed parameter as a function of position through: (i) scattering (e.g., back-scattering) based approaches (for example, known Rayleigh scattering, Brillouin scattering, or Raman scattering approaches), or (ii) a discrete set of sampling points through the use of multiple sensor elements provided in an array, such as fiber Bragg gratings inscribed in the sensor core along with a functionalized overcoating. An example of such a back-scattering approach is described in R. G. Duncan, B. J. Soller, D. K. Gifford, S. T. Kreger, R. J. Seeley, A. K. Sang, M. S. Wolfe, and M. E. Froggatt, "OFDR-Based Distributed Sensing and Fault Detection for Single- and Multi-Mode Avionics Fiber-Optics", available at <http://lunainc.com/wp-content/uploads/2012/08/OFDR-Based-Distributed-Sensing.pdf>. Examples of the use of multiple sensor elements are described in L. C. G. Valente et al., "Time and Wavelength Multiplexing of Fiber Bragg Grating Sensors Using a Commercial OTDR", Optical Fiber Sensors Conference Technical Digest, May 10, 2002, Portland, Oregon.

[27] Unlike localized fiber optic sensors such as fiber Bragg gratings, non-localized distributed sensors offer the unique characteristic of being able to use the entire length of an un-modified optical fiber as a sensor, allowing the measurements of thousands of points along the fiber. The most developed technologies of distributed fiber optic sensors, which have sufficient spatial resolutions and can perform both strain and temperature measurements, are based on Brillouin scattering and Rayleigh scattering.

In Brillouin scattering, as a nonlinear interaction between the light and the silica material, if an intense optical pulse is launched into a fiber, it will generate

lattice vibration with characteristic frequency Ω_B in the form of pressure wave (i.e., a phonon), which periodically modulates density of the fiber. This wave can be treated as transient gratings in the fiber traveling at speed of the sounds V_a associated with the acoustic wave frequency Ω_B . When these moving transient gratings diffract the probing light, the frequency of the probing light will experience a Doppler frequency shift of $\pm\Omega_B$, depending on relative directions between the sound wave and probing light. Since the acoustic frequency Ω_B depends on the temperature or strain in optical fibers, the measurement of Ω_B as the function of travel time t of optical pulse provides spatially resolved strain or temperature measurement. From this basic principle, the spatial resolution of the Brillouin scattering depends on the pump pulse width. An optical time domain reflectometry technique (OTDR) is usually employed, in which the system is probed by fast laser pulses and the spatial resolution is limited by the pulse duration. Typically, optical pulses at 1 GHz are used, which lead to typical spatial resolution of OTDR around ~ 30 cm to 1 meter. The Brillouin technique can achieve >50 km level distributed measurement with 1-m level spatial resolution.

[28] Rayleigh scattering is an elastic scattering of light by subwavelength-size particles during light propagation. In optical fibers, the density fluctuations of silica material give rise to the Rayleigh scattering loss. The scattering coefficient in optical fiber can be estimated as:

$$\alpha(z)_{\text{Rayleigh}} = \frac{8\pi}{3\lambda^4} [n(z)^8 p^2 (kT_f) \beta],$$

where $n(z)$ is the refractive index profile, p is the photo-elastic coefficient, k is the Boltzmann constant, β is the isothermal compressibility, and T_f is the fictive temperature at which the density fluctuations are frozen. Rayleigh backscatter in an optical fiber is caused by random fluctuations in the index profile $n(z)$ along the fiber length, which can be modeled as a very weak and long FBG with random period. When external stimulus (T , strain) changes the local index, it changes the local reflection spectrum, which can be used as a sensing signal measured by an Optical Frequency Domain Reflectometry (OFDR) technique.

[29] A primary challenge of distributed sensing approaches employing multiple sensor elements, such as fiber Bragg gratings, provided in an array in high

temperature environments, such as a nuclear reactor, is the stability of fiber Bragg gratings in fabricated devices. Recent developments in generating high temperature stable fiber gratings can potentially help to overcome this latter technological challenge, and, according to an aspect of the disclosed concept, may be used in connection with the various embodiments described herein. Example of such a high temperature stable fiber gratings are described in United States Patent Application Publication Number 2014/0321798, entitled “Optical Sensor Employing a Refractive Index Engineered Metal Oxide Material”, the disclosure of which is incorporated herein by reference, and in Zsolt L. Poole, Paul Ohodnicki, Michael Buric, Aidong Yan, Shaymaa Riyadh, Yuankun Lin, and Kevin P. Chen, “Block Copolymer Assisted Refractive Index Engineering Of Metal Oxides For Applications In Optical Sensing,” Proc. SPIE 9161, Nanophotonic Materials XI, 91610P (September 10, 2014), and T. Chen, R. Chen, C. Jewart, B. Zhang, K. Cook, J. Canning, and K. P. Chen, “Regenerated Gratings in Air-Hole Microstructured Fibers for High-Temperature Pressure Sensing”, Optics Letters 36 (18), 3542-4 (2011), and Y. K. Cheong, W. Y. Chong, S. S. Chong, K. S. Lim, and H. Ahmad, “Regenerated Type-IIa Fibre Bragg Grating from a Ge-B Codoped Fiber via Thermal Activation”, Optics & Laser Technology 62, 69-72 (2014).

[30] FIG. 1 is a schematic diagram of a sensing system 2 that may be implemented in conjunction with a structure 4 of an industrial, commercial or residential building, such as, without limitation, a nuclear reactor vessel. In the exemplary embodiment, structure 4 is a nuclear reactor vessel. Sensing system 2 is structured to enable continuous distributed sensing of one or more parameters within structure 4, such as a physical parameter (e.g., radiation, temperature, strain, pressure, liquid levels) or a chemical parameter (e.g., radical chemical species (such as hydrogen) concentration). In the illustrated embodiment, sensing system 2 includes a cable device 6 described in greater detail below. Sensing system 2 also includes a laser source 20, a circulator 22, an optical signal analyzer, optical backscatter time/frequency domain reflectometer 24, and transmission fibers 26 and 28.

[31] Cable device 6 is implemented in accordance with the disclosed concept. Cable device 6 includes a sheath member 8 that may be, for example and without limitation, a flexible polyvinylchloride (PVC) conduit or tube. Cable device 6 also includes first and second electrical cables 10 and 12, which are provided within

sheath member 8. In the exemplary embodiment, each electrical cable 10, 12 is structured to be functional within a harsh environment such as a nuclear reactor vessel, and is resistant to and can tolerate radiation up to 100 kGy (10 MRad).

[32] As seen in FIG. 1, cable device 6 also includes an optical fiber sensing member 14. Optical fiber sensing member 14 is a functionalized optical fiber based sensor device that includes an in-fiber sensing element 16. Optical fiber sensing member 14 is structured to enable continuous distributed sensing of one or more parameters within structure 4 as described above using a back-scattering based interrogation approach, for example as described herein. In the exemplary embodiment, in-fiber sensing element 16 is a monolithic in-fiber sensing element. In alternative embodiments, in-fiber sensing element 16 is an array of discrete sensor elements, such as an array of high temperature stable Fiber-Bragg grating sensor elements.

[33] In operation, in-fiber sensing element 16 exhibits a change in optical absorption in the presence of a particular parameter of interest, e.g., radiation, temperature, strain, or hydrogen concentration. The change in optical absorption is correlated with the parameter of interest in well-designed sensor elements, which results in optical transmission over a range of wavelengths which is correlated to the parameter of interest. Consequently, the backscattering which is intrinsic to all optical materials (including in-fiber sensing element 16) is also correlated in intensity to the parameter of interest. When interrogated with an optical backscattering based distributed interrogator, such as optical signal analyzer, optical backscatter time/frequency domain reflectometer 24, the parameter of interest may further be correlated with physical distance or position along optical fiber sensing member 14. In combination with appropriate calibration techniques, the approach described can allow for quantification of the absolute magnitude and/or gradient in the parameter of interest.

[34] In one non-limiting example, optical fiber sensing member 14 is sensitive to and able to sense gamma radiation (e.g., from 1 Gy to > 10,000 Gy), and thus the parameter of interest is radiation level or absorption. Such an exemplary optical fiber sensing member 14 could be, without limitation, an optical fiber doped with aluminum.

- [35] In another non-limiting example, optical fiber sensing member 14 is radiation resistant and is structured to measure a physical parameter such as strain or temperature. Such an exemplary optical fiber sensing member 14 could be, without limitation, an air-hole photonic crystal fiber, a pure silica core fiber, or an F-doped fiber.
- [36] In still another non-limiting example, optical fiber sensing member 14 is radiation resistant and sensitive to chemical species. As such, optical fiber sensing member 14 is structured to enable measurement of a chemical parameter such as radical chemical species (e.g., hydrogen) concentration. Such an exemplary optical fiber sensing member 14 could be, without limitation, a radiation-resistant fiber with a chemical reactive fiber coating, a D-shaped optical fiber wherein the fiber core is exposed to ambient atmosphere, or an optical fiber with diffusive (e.g., random air-hole) cladding that is structured to allow chemical species to be permeated therethrough to interact with the fiber core.
- [37] In the exemplary embodiment, optical fiber sensing member 14 is protected by an appropriate polymer tube to reduce friction with electrical cables 10, 12 .
- [38] FIG. 2 is a schematic diagram of a sensing system 2' that may be implemented in conjunction with structure 4 according to an alternative embodiment. Sensing system 2' is similar to sensing system 2 (like components are labelled with like reference numerals), and is structured to enable continuous distributed sensing of multiple parameters within structure 4. In the illustrated embodiment, sensing system 2' includes an alternative cable device 6' that is similar to cable device 6, except that it includes a plurality of optical fiber sensing members 14 structured to measure different parameters. An optical switch 30 is provided to enable selection from among the plurality of measured parameters.
- [39] As noted elsewhere herein, the disclosed concept may also use single point sensing to sense such parameters. FIG. 3 is a schematic diagram of a sensing system 2'' that may be implemented in conjunction with structure 4 according to another alternative embodiment that employs single point sensing. This embodiment includes an alternative cable device 6'' that is similar to cable device 6, except that it includes an alternative optical fiber sensing member 32 that is a functionalized optical

fiber based sensor device. Optical fiber sensing member 32, however, includes a single point in-fiber sensing element 34.

[40] Single point in-fiber sensing element 34 may be any of a number of known or hereafter developed in-fiber sensing elements. For example, a suitable in-fiber sensing element 34 may be a silica-based optical fiber with the cladding removed and a SrTiO₃ or La-doped SrTiO₃ thin film coated on the exposed core as described in United States Patent Application Serial No. 14/335,149, entitled “Electronically Conductive Perovskite-Based Oxide Nanoparticles and Films for Optical Sensing Applications” and filed July 18, 2014, the disclosure of which is incorporated herein by reference. As another example, a suitable in-fiber sensing element 34 may be a TiO₂, Nb-doped TiO₂, or Pd-doped TiO₂ thin film coated optical fiber as described in United States Patent No. 8,638,440, entitled “Plasmonic Transparent Conducting Metal Oxide Nanoparticles and Films for Optical Sensing Applications”. Another suitable in-fiber sensing element 34 may be achieved through the incorporation of gold nanoparticles within inert matrix materials of SiO₂, Al₂O₃, and Si₃N₄ as a thin film coated on an optical fiber as described in United States Patent No. 8,411,275, entitled “Nanocomposite Thin Films for High Temperature Optical Gas Sensing of Hydrogen”. The disclosures of these documents are incorporated herein by reference in all cases.

[41] As seen in FIG. 3, sensing system 2" further includes a light source 36, such as a laser, and a detector 38. In operation, source light is introduced into optical fiber sensing member 32 from light source 36, and, in response thereto, light is transmitted through optical fiber sensing member 32 and received at detector 38. Optical fiber sensing member 32 and in-fiber sensing element 34 are structured such that one or more optical properties thereof will change depending upon the parameter of interest, such as those described elsewhere herein. As a result, one or more properties of the light transmitted through optical fiber sensing member 32 and detected by detector 38 will, as is known in the art, be indicative of the parameter of interest around in-fiber sensing element 34 at any particular time.

[42] In the embodiments described herein, the fibers can be connected with the monitoring device for continuous monitoring, or can be packed inside the sheath member but kept offline (spare fiber) without continuous monitoring to be checked intermittently.

[43] In the claims, any reference signs placed between parentheses shall not be construed as limiting the claim. The word “comprising” or “including” does not exclude the presence of elements or steps other than those listed in a claim. In a device claim enumerating several means, several of these means may be embodied by one and the same item of hardware. The word “a” or “an” preceding an element does not exclude the presence of a plurality of such elements. In any device claim enumerating several means, several of these means may be embodied by one and the same item of hardware. The mere fact that certain elements are recited in mutually different dependent claims does not indicate that these elements cannot be used in combination.

[44] Although the invention has been described in detail for the purpose of illustration based on what is currently considered to be the most practical and preferred embodiments, it is to be understood that such detail is solely for that purpose and that the invention is not limited to the disclosed embodiments, but, on the contrary, is intended to cover modifications and equivalent arrangements that are within the spirit and scope of the appended claims. For example, it is to be understood that the present invention contemplates that, to the extent possible, one or more features of any embodiment can be combined with one or more features of any other embodiment.

What is claimed is:

1. A cable device, comprising:
a sheath member;
a number of electrical cables provided within the sheath member; and
an optical fiber sensing member provided within the sheath member,
wherein the optical fiber sensing member comprises a functionalized optical fiber based sensor device structured to exhibit a change in one or more optical properties in response to changes in a parameter of interest.
2. The cable device according to claim 1, wherein the parameter of interest is a physical parameter.
3. The cable device according to claim 2, wherein the physical parameter is one of radiation, temperature, strain, pressure and liquid level.
4. The cable device according to claim 1, wherein the parameter of interest is a chemical parameter.
5. The cable device according to claim 1, wherein the one or more optical parameters change responsive to gamma radiation.
6. The cable device according to claim 5, wherein the one or more optical parameters change responsive to gamma radiation from 1 Gy to greater than 10,000 Gy.
7. The cable device according to claim 5, wherein the optical fiber sensing member comprises an optical fiber doped with aluminum.
8. The cable device according to claim 1, wherein the optical fiber sensing member is radiation resistant and the one or more optical parameters change responsive to a physical parameter other than radiation or presence of a chemical species.

9. The cable device according to claim 1, wherein the optical fiber sensing member is surrounded by a polymer to reduce friction with the number of electrical cables.

10. The cable device according to claim 1, further comprising a second optical fiber sensing member provided within the sheath member, wherein the second optical fiber sensing member comprises a functionalized optical fiber based sensor device structured to exhibit a change in one or more second optical properties in response to changes in a second parameter of interest that is different than the parameter of interest.

11. A sensing system employing the cable device according to claim 1, wherein the optical fiber sensing member includes a single point in-fiber sensing element, and wherein the sensing system is structured to measure the parameter of at a particular location along the cable device.

12. A sensing system employing the cable device according to claim 1, wherein the sensing system is structured to implement distributed sensing of the parameter of interest along the cable device.

13. The sensing system according to claim 12, wherein the optical fiber sensing member includes a monolithic in-fiber sensing element and wherein the sensing system is structured to implement the distributed sensing using a scattering based interrogation approach.

14. The sensing system according to claim 13, wherein the scattering based interrogation approach is a back scattering based interrogation approach.

15. The sensing system according to claim 12, wherein the optical fiber sensing member includes a plurality of in-fiber sensing elements arranged in series.

16. The sensing system according to claim 15, wherein each of the in-fiber sensing elements includes a high-temperature stable fiber Bragg grating.

17. A sensing method employing the cable device according to claim 1, comprising:

introducing a source light into the optical fiber sensing member;
detecting sensing light generated in response to the source light; and
determining a value for the parameter of interest using the detected sensing light.

18. A method of sensing radiation within a structure, comprising:
introducing a source light into an optical fiber sensing member provided within the structure, wherein the optical fiber sensing member comprises a functionalized optical fiber based sensor device structured to exhibit a change in one or more optical properties in response to radiation;
detecting sensing light generated in response to the source light; and
determining a radiation level at a plurality of locations within the structure and along the optical fiber sensing member using the detected sensing light and a distributed sensing scheme.

19. The method according to claim 18, wherein the optical fiber sensing member includes a monolithic in-fiber sensing element and wherein the distributed sensing scheme is a scattering based interrogation approach.

20. The method according to claim 19, wherein the scattering based interrogation approach is a back scattering based interrogation approach.

21. The method according to claim 18, wherein the optical fiber sensing member includes a plurality of in-fiber sensing elements arranged in series.

22. The sensing system according to claim 21, wherein each of the in-fiber sensing elements includes a high-temperature stable fiber Bragg grating.

23. The method according to claim 18, wherein the radiation is gamma radiation.
24. The method according to claim 23, wherein the one or more optical parameters change responsive to gamma radiation from 1 Gy to greater than 10,000 Gy.
25. The method according to claim 18, wherein the optical fiber sensing member comprises an optical fiber doped with aluminum.
26. A system for sensing radiation in a structure, comprising:
an optical fiber sensing member provided within the structure, wherein the optical fiber sensing member comprises a functionalized optical fiber based sensor device structured to exhibit a change in one or more optical properties in response to radiation;
a light source structured to introduce a source light into an optical fiber sensing member; and
an optical signal analyzing device structured and configured to detect sensing light generated in response to the source light and determine a radiation level at a plurality of locations within the structure and along the optical fiber sensing member using the detected sensing light and a distributed sensing scheme.
27. The system according to claim 26, wherein the optical fiber sensing member includes a monolithic in-fiber sensing element and wherein the distributed sensing scheme is a scattering based interrogation approach.
28. The system according to claim 27, wherein the scattering based interrogation approach is a back scattering based interrogation approach.
29. The system according to claim 26, wherein the optical fiber sensing member includes a plurality of in-fiber sensing elements arranged in series.

30. The system according to claim 26, wherein the optical fiber sensing member comprises an optical fiber doped with aluminum.

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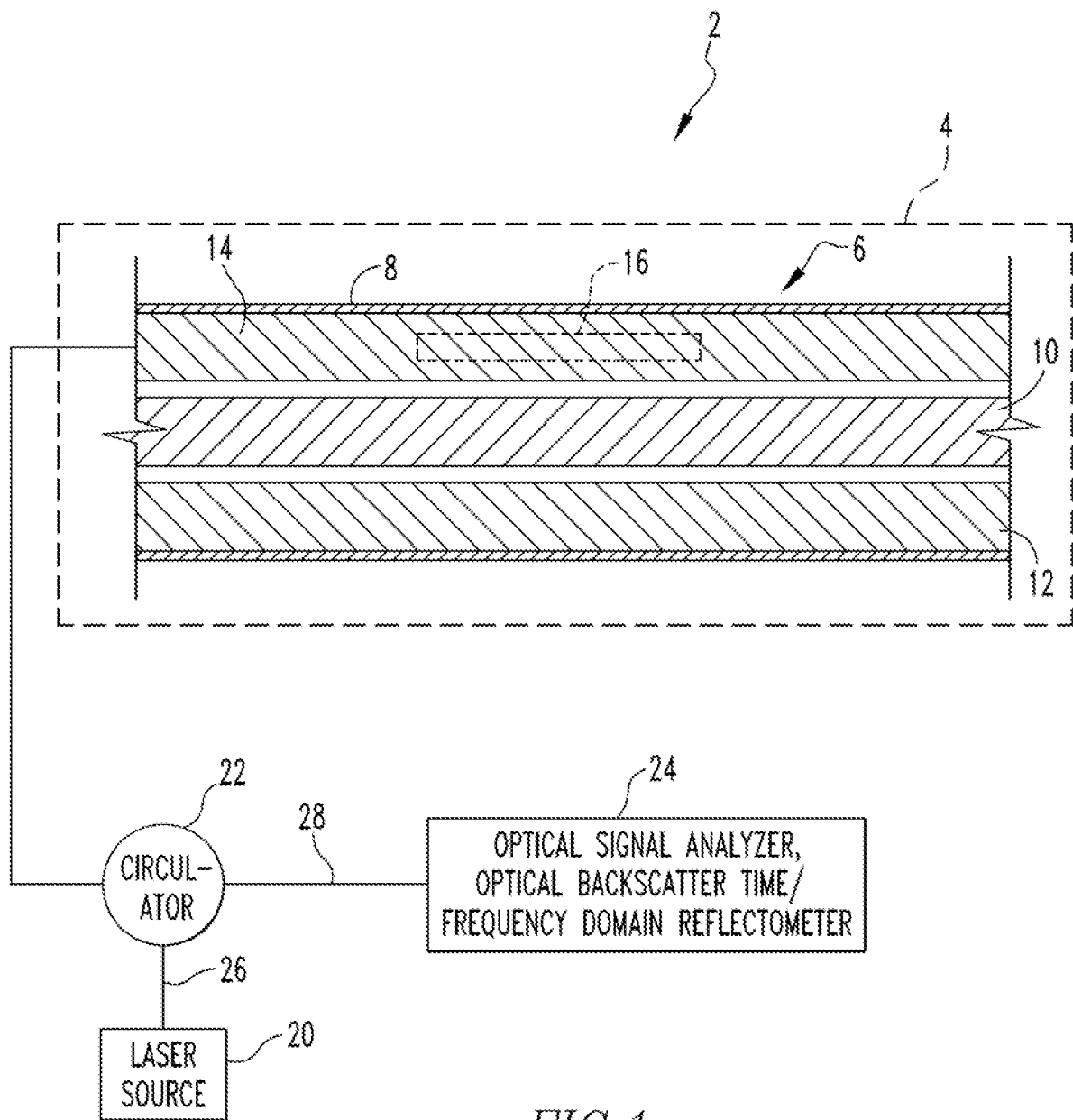
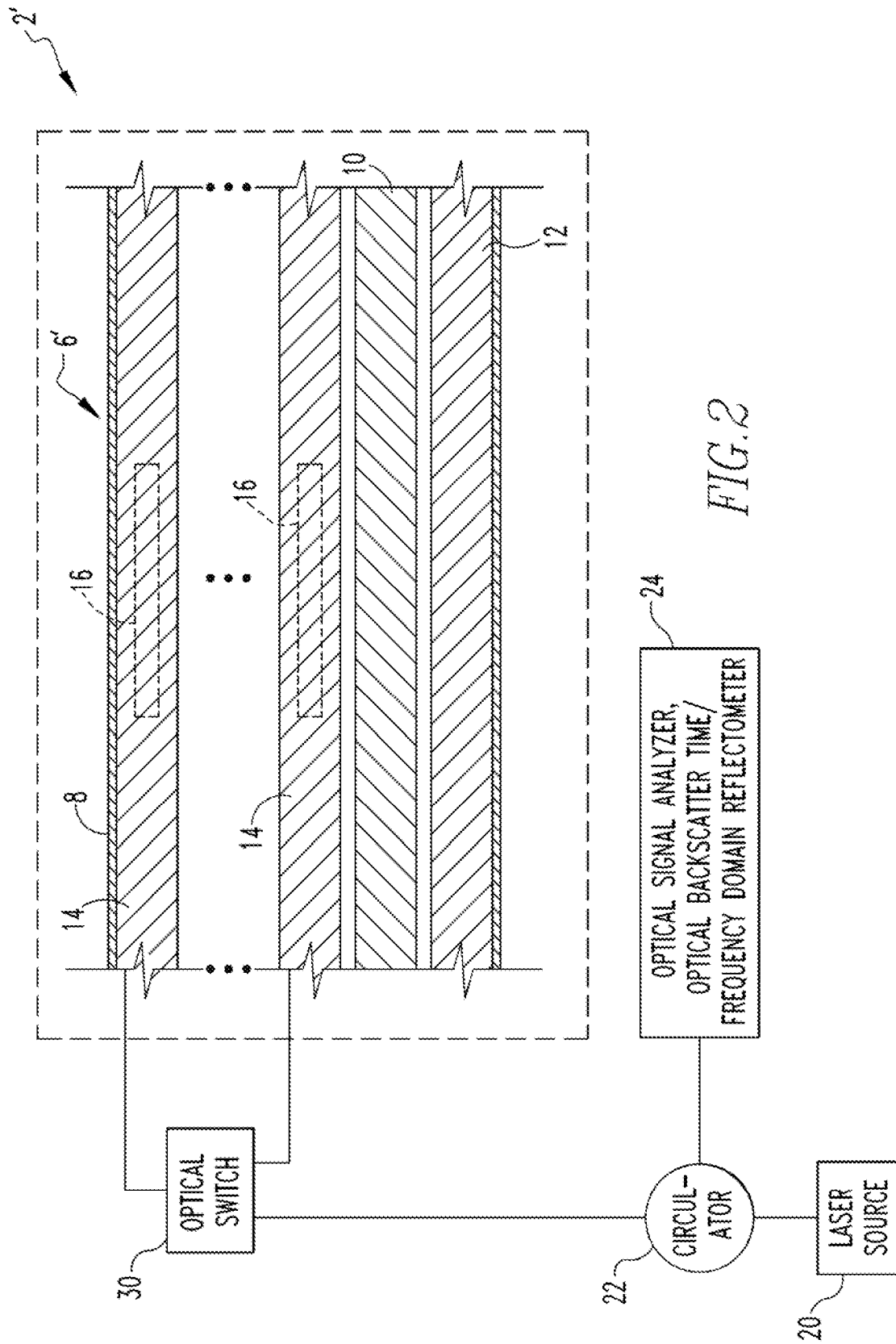


FIG. 1



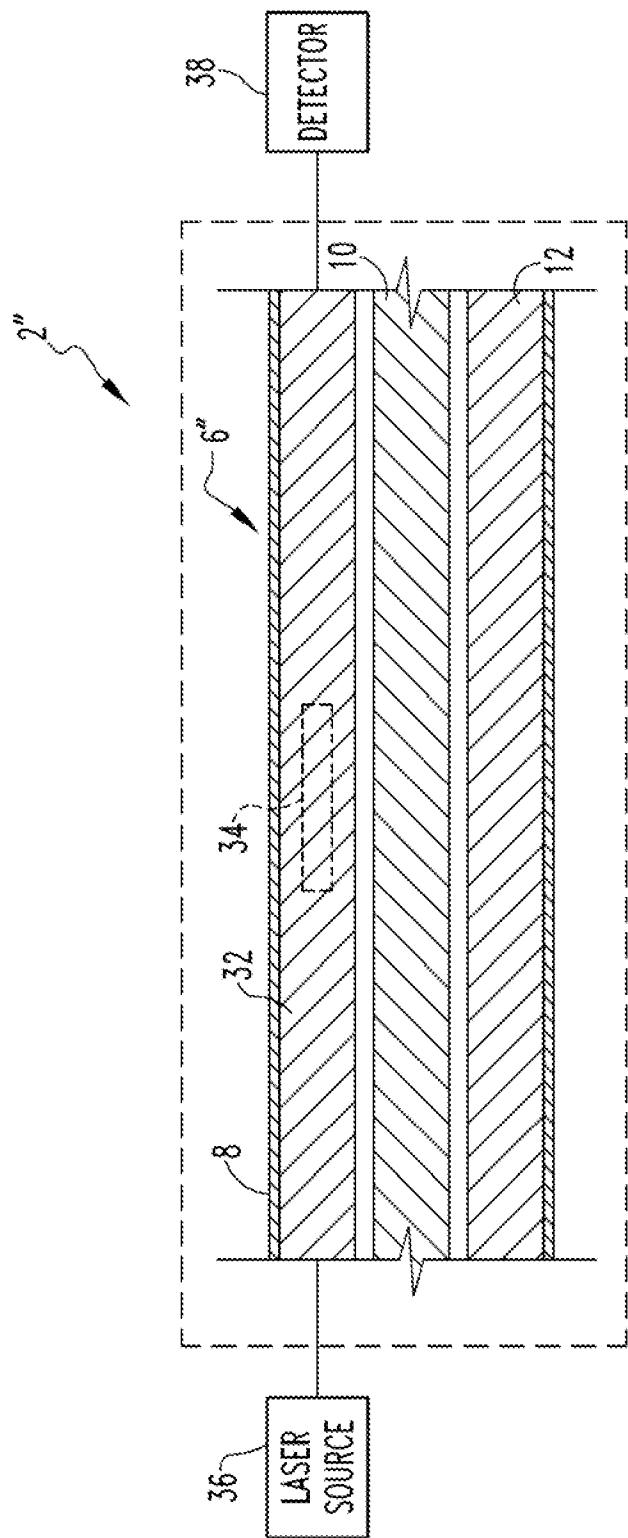


FIG. 3

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Group I, claims 1-16 are directed to a cable device and a sensing system employing the cable device.

Group II, claims 17-30 are directed to a method and a system for sensing radiation within a structure.

Since the above mentioned groups of claims do not share any of the technical features identified, a technically special relationship between the inventions does not exist. Accordingly the claims do not relate to one invention or to a single inventive concept, a priori.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-16

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/023147**A. CLASSIFICATION OF SUBJECT MATTER****H01B 9/00(2006.01)i, H01B 7/17(2006.01)i, H01B 9/02(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01B 9/00; G01L 1/24; C03C 25/10; G01K 11/12; G01N 21/84; G01T 1/00; H01B 11/22; G01R 19/00; G02B 6/44; H01B 7/17; H01B 9/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: cable, sheath, optical fiber, sensor, radiation

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2002-0085819 A1 (THOMAS R. STOTTEMYER et al.) 04 July 2002 See paragraphs [16]-[23], claims 1-5 and figures 1-3.	1-3, 8, 10-16
Y		4-7, 9
Y	US 2014-0321798 A1 (UNIVERSITY OF PITTSBURGH-OF THE COMMONWEALTH SYSTEM OF HIGHER EDUCATION et al.) 30 October 2014 See paragraphs [41]-[46] and figure 5.	4
Y	JP 05-296856 A (HITACHI CABLE LTD.) 12 November 1993 See paragraphs [17]-[20] and figure 1.	5-7
Y	US 2012-0082422 A1 (SARCHI et al.) 05 April 2012 See paragraphs [98]-[115] and figures 1a-2b.	9
A	CN 204945215 U (ZHANG HAO et al.) 06 January 2016 See claims 1-4, 10 and figures 1-6.	1-16



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

19 July 2017 (19.07.2017)

Date of mailing of the international search report

19 July 2017 (19.07.2017)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2017/023147

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2002-0085819 A1	04/07/2002	US 6466719 B2	15/10/2002
US 2014-0321798 A1	30/10/2014	None	
JP 05-296856 A	12/11/1993	None	
US 2012-0082422 A1	05/04/2012	AU 2009-346811 A1	08/12/2011
		AU 2009-346811 B2	10/09/2015
		BR PI0924731 A2	26/01/2016
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		EP 2555205 A1	06/02/2013
		RU 2011153385 A	10/07/2013
		RU 2510865 C2	10/04/2014
		US 8953915 B2	10/02/2015
		WO 2010-136062 A1	02/12/2010
CN 204945215 U	06/01/2016	None	