

SENSOR AND METHOD OF MANUFACTURING THE SAME, AND SYSTEM FOR
DETECTING A PARTIAL DISCHARGE SIGNAL AND A METHOD OF FORMING
THE SAME

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Cross-Reference To Related Application

[0001] This application claims the benefit of priority of Singapore patent application No. 201005144-9, filed 16 July 2010, the content of it being hereby incorporated by reference in its entirety for all purposes.

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Technical Field

[0002] Various embodiments relate to a sensor and a method of manufacturing the sensor. Various embodiments further relate to a system for detecting a partial discharge signal, a method of forming the system for detecting a partial discharge signal and a method of detecting a partial discharge signal.

Background

[0003] High voltage equipment, such as metal clad switchgears, transformers, and gas insulated switchgears (GIS) are key assets in a wide range of industries. The insulated materials used in this high voltage equipment are capable of withstanding high voltages. However, as the material decays over time, the equipment may be damaged, which will result in disruption of power generation, usage, and manufacturing processes.

[0004] A partial discharge (PD) is a localised dielectric breakdown of a small portion of a solid or liquid electrical insulation system under high voltage stress.

[0005] There are three kinds of methods which can be applied to detect the PD signals from a power equipment. These include an electrical method, a non-electrical method, and a hybrid electrical-optical method.

[0006] In the electrical method, the couple capacitor is not suitable for online detection and the Rogowski coil is easily interfered by other signals. As for the non-electrical

method, acoustic detection and optical detection are used. The ultrasonic microphone can detect PD signals which is transmitted via air from the equipment. However, the PD signals cannot be detected if PD sources are caused by media inside the equipment. As for optical detections, one such detection is based on temperature measurement on the surfaces of the equipment, where the PD results in an increase in temperature. However, when the PD occurs inside the equipment, this method is not effective.

[0007] In the hybrid electrical-optical method, a passive sensing system or an active sensing system may be used. The passive sensing system is comprised of a Fabry-Perot semiconductor laser, where the system has high noise and low sensitivity. On the other hand, the active sensing system uses a fiber powering technique to properly polarize the laser and another optical fiber to carry the high optical power from a 1480 nm optical source to the photovoltaic converter. Although this system has high sensitivity, the system is complex and unsuitable for array application.

15 Summary

[0008] According to an embodiment, a sensor is provided. The sensor may include an antenna configured to receive a partial discharge signal, and a vertical-cavity surface-emitting laser coupled to the antenna, wherein the vertical-cavity surface-emitting laser is configured to convert the received partial discharge signal into an optical signal.

[0009] According to an embodiment, a system for detecting a partial discharge signal is provided. The system may include at least one sensor as described above, and at least one detector coupled to the at least one sensor, wherein the at least one detector is configured to detect the optical signal from the at least one sensor and convert the optical signal into an electrical signal.

[0010] According to an embodiment, a method of forming a sensor is provided. The method may include providing an antenna configured to receive a partial discharge signal, and coupling a vertical-cavity surface-emitting laser to the antenna, wherein the vertical-cavity surface-emitting laser is configured to convert the received partial discharge signal into an optical signal.

[0011] According to an embodiment, a method of forming a system for detecting a partial discharge signal is provided. The method may include forming at least one sensor using the method as described above, and coupling at least one detector to the at least one sensor, wherein the at least one detector is configured to detect the optical signal from the
5 at least one sensor and convert the optical signal into an electrical signal.

[0012] According to an embodiment, a method of detecting a partial discharge signal is provided. The method may include receiving a partial discharge signal with an antenna, and converting the received partial discharge signal into an optical signal with a vertical-cavity surface-emitting laser coupled to the antenna.

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Brief Description of the Drawings

[0013] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis
15 instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0014] FIG. 1A shows a schematic block diagram of a sensor, according to various embodiments.

20 [0015] FIG. 1B shows a schematic block diagram of a sensor, according to various embodiments.

[0016] FIG. 1C shows a schematic block diagram of a system for detecting a partial discharge signal, according to various embodiments.

25 [0017] FIG. 1D shows a schematic block diagram of a system for detecting a partial discharge signal, according to various embodiments.

[0018] FIG. 2A shows a flow chart illustrating a method of forming a sensor, according to various embodiments.

[0019] FIG. 2B shows a flow chart illustrating a method of forming a system for detecting a partial discharge signal, according to various embodiments.

30 [0020] FIG. 2C shows a flow chart illustrating a method of detecting a partial discharge signal, according to various embodiments.

[0021] FIG. 3 shows a schematic view of a partial discharge sensor, according to various embodiments.

[0022] FIG. 4 shows a schematic view of a partial discharge sensor, according to various embodiments.

5 [0023] FIG. 5 shows a schematic view of a partial discharge sensor, according to various embodiments.

[0024] FIG. 6A shows a schematic view of an antenna, according to various embodiments.

10 [0025] FIG. 6B shows a schematic view of a dual-band antenna, according to various embodiments.

[0026] FIG. 7 shows a schematic view of a system for detecting a partial discharge signal, according to various embodiments.

[0027] FIG. 8 shows a schematic view of a system for detecting a partial discharge signal, according to various embodiments.

15 [0028] FIG. 9 shows a schematic view of a system for detecting a partial discharge signal, according to various embodiments.

[0029] FIG. 10 shows a schematic view of a system for detecting a partial discharge signal, according to various embodiments.

20 [0030] FIG. 11 shows a schematic view of a system for detecting a partial discharge signal, according to various embodiments.

[0031] FIG. 12 shows photographs of a partial discharge sensor of various embodiments.

[0032] FIG. 13 shows a partial discharge signal, according to various embodiments.

[0033] FIG. 14 shows a plot of a partial discharge signal, according to various embodiments.

25 [0034] FIG. 15 shows a plot of a partial discharge signal in time domain, according to various embodiments.

[0035] FIG. 16 shows a photograph of a system for detecting partial discharge signals, according to various embodiments.

30 [0036] FIG. 17 shows a schematic perspective view of a vertical-cavity surface-emitting laser (VCSEL), according to various embodiments.

Detailed Description

[0037] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new
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embodiments.

[0038] Various embodiments provide a sensor and a system including a sensor or an array of sensors, based on radio frequency (RF) and optical technologies, for detecting partial discharge signal or signals.

[0039] Various embodiments provide a partial discharge (PD) sensor and a system
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including a partial discharge sensor or an array of partial discharge sensors, based on radio frequency (RF) and optical technologies.

[0040] The system may be a simple and low cost partial discharge measurement system, for example a partial discharge (PD) sensor array system, which may be used to detect and/or measure partial discharge signal or signals from an equipment, for example a power equipment such as metal clad switchgears, gas insulated switchgears (GIS), power cables and transformers. Therefore, the system of various embodiments may be used for health monitoring or status monitoring of the power equipment or devices so as to determine or assess whether any maintenance of the equipment is required. The system may have high sensitivity and may use a single optical fiber or a single fiber cable for
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online monitoring.

[0041] Various embodiments may provide a system including an array of partial discharge sensors for detecting partial discharge signals from a power equipment at various locations of the power equipment. As an array of partial discharge sensors is provided, partial discharge signals may be detected and/or measured at various locations
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of the power equipment by positioning the array of partial discharge sensors at the

corresponding various locations. For example, a respective partial discharge sensor of the sensor array may be provided at a respective location.

5 [0042] In various embodiments, two or more partial discharge sensors of the sensor array may be provided at a particular location to measure the partial discharge signal from that location of the equipment, to obtain two or more measurements of the partial discharge signal, for example to obtain an average measurement or reading of the partial discharge signal and/or to increase the reliability of the measurements.

[0043] In the context of various embodiments, the array of partial discharge sensors may include two, three, four, five or any higher number of partial discharge sensors.

10 [0044] In various embodiments, each partial discharge (PD) sensor includes one or more antennas configured to receive the partial discharge signal or signals, and a vertical-cavity surface-emitting laser (VCSEL) configured to convert the signal or signals received by the one or more antennas into one or more optical signals.

15 [0045] In various embodiments of the partial discharge sensor system or sensor array system, one or more partial discharge (PD) sensors may be provided. The partial discharge signals received by the antennas of the sensor array may have frequencies in a particular frequency range. The partial discharge signals may then be converted to optical signals by the corresponding vertical-cavity surface-emitting laser (VCSEL). The converted optical signals may have the same or different frequencies (or correspondingly
20 the same or different wavelengths) as that of the partial discharge signals.

[0046] In various embodiments, each laser may be operated at the same or different wavelengths. This may mean that each laser may be optically pumped by a light source of the same or different wavelengths and/or that each laser may emit light of the same or different wavelengths.

25 [0047] In embodiments where the laser (e.g. VCSEL) is operated at different wavelengths, and correspondingly the partial discharge signals are converted into optical signals with different wavelengths, the system of various embodiments may be rendered effectively self-multiplexed by using an optical fiber cable having multi-individual optical fibers for propagation of the optical signals or by using a single optical fiber and
30 facilitated by couplers (e.g. 1×2 couplers), such as fiber couplers, to couple or combine

the optical signals for propagation using the single optical fiber, and then demultiplexed via a wavelength-division multiplexing (WDM) demultiplexer.

[0048] In various embodiments of the partial discharge sensor system or sensor array system, the optical signals or the demultiplexed optical signals may then be detected and converted into electrical signals by a detector array, followed by data acquisition, processing and analysis in order to determine whether the equipment (e.g. power equipment) needs to be maintained, serviced and/or repaired.

[0049] In various embodiment, the partial discharge sensor or sensor array and the system including the partial discharge sensor or sensor array, may be capable of long distance online monitoring of partial discharge signal or signals, for example from a power equipment.

[0050] In various embodiments, the partial discharge sensor or sensor array and the system including the partial discharge sensor or sensor array, may provide simpler signal interrogation and a simpler system configuration which may translate to a more cost effective solution.

[0051] In various embodiments, the partial discharge sensor or sensor array and the system including the partial discharge sensor or sensor array may generate less noise or minimal noise and may provide non-intrusive measurements or detections.

[0052] In the context of various embodiments, a simple partial discharge sensor array system using hybrid RF and optical techniques may be provided for detection or measurement of partial discharge signals for a power equipment. The partial discharge sensor array system may include one or more of the following:

- a partial discharge (PD) array having a plurality of PD sensors (e.g. n number of PD sensors) according to various embodiments, where one or more antennas are used to receive the PD signals from an equipment (e.g. power equipment), the one or more antennas being connected to one or more electrically biased vertical-cavity surface-emitting lasers directly or by using an RF cable, in order to convert the PD signals into optical signals, which are then transmitted via one or more optical fibers;
- an optical fiber cable with multi-individual fibers or a single fiber cable with $(n-1)$ tap couplers to connect to the optical fibers of the partial discharge sensors;

- a detector array with optical fibers which are connected to the optical fiber cable with multi-individual fibers, or connected to the single fiber cable with $(n-1)$ tap couplers via a demultiplexer;
- a data acquisition means for acquiring electrical signals from the detector array; and
- 5 - a processing device (e.g. a computer) for analysing the acquired electrical signals and generating a report.

[0053] In order that the invention may be readily understood and put into practical effect, particular embodiments will now be described by way of examples and not limitations, and with reference to the figures.

10 **[0054]** FIG. 1A shows a schematic block diagram of a sensor 100, according to various embodiments. The sensor 100 may be a partial discharge sensor. The sensor 100 includes an antenna 102 configured to receive a partial discharge signal, and a vertical-cavity surface-emitting laser 104 coupled to the antenna 102, wherein the vertical-cavity surface-emitting laser 104 is configured to convert the received partial discharge signal
15 into an optical signal.

[0055] The line represented as 106 represents the coupling between the antenna 102 and the vertical-cavity surface-emitting laser 104. The coupling 106 may be such that the vertical-cavity surface-emitting laser 104 is connected directly with or is integrated in the antenna 102 or that the vertical-cavity surface-emitting laser 104 is coupled to the
20 antenna via an electrical interconnection, such as a radio frequency (RF) cable.

[0056] FIG. 1B shows a schematic block diagram of a sensor 120, according to various embodiments. The sensor 120 may be a partial discharge sensor. The sensor 120 includes an antenna 102 and a vertical-cavity surface-emitting laser 104 coupled to the antenna 102, which may be similar to the embodiment as described in the context of FIG. 1A.

25 **[0057]** In the sensor 120, the vertical-cavity surface-emitting laser 104 may include a SubMiniature version A (SMA) connector or Bayonet Neill-Concelman (BNC) connector coupled to an anode and a cathode of the vertical-cavity surface-emitting laser 104 for coupling to the RF cable. The SMA connector and the BNC connector are types of RF connectors.

30 **[0058]** The sensor 120 may further include a biasing circuit 122 coupled to the vertical-cavity surface-emitting laser 104. The sensor 120 may further include an amplifying

circuit 124 coupled to the vertical-cavity surface-emitting laser 104 to amplify the signal from the antenna 102 (e.g. the partial discharge signal received by the antenna 102). The amplifying circuit 124 may be coupled in between the antenna 102 and the vertical-cavity surface-emitting laser 104. In various embodiments, the amplifying circuit 124 may or
5 may not be used.

[0059] The sensor 120 may further include an optical waveguide 126 coupled to the vertical-cavity surface-emitting laser 104, the optical waveguide 126 configured to transmit the optical signal. The optical waveguide 126 may be an optical fiber.

[0060] The sensor 120 may further include a second antenna 128 coupled to the vertical-
10 cavity surface-emitting laser 104.

[0061] FIG. 1C shows a schematic block diagram of a system 140 for detecting a partial discharge signal, according to various embodiments. The system includes at least one sensor 142, and at least one detector 144 coupled to the at least one sensor 142, wherein the at least one detector 144 is configured to detect the optical signal from the at least one
15 sensor 142 and convert the optical signal into an electrical signal. In various embodiments, the at least one sensor 142 may be of the embodiment of FIGS 1A or 1B. The at least one sensor 142 may be a partial discharge sensor.

[0062] The line represented as 146 represents the coupling between the at least one sensor 142 and the at least one detector 144. The coupling 146 may be optical coupling,
20 for example an optical fiber. The coupling 146 may be a direct coupling or an indirect coupling with one or more intermediate modules or elements, for example a demultiplexer.

[0063] FIG. 1D shows a schematic block diagram of a system 160 for detecting a partial discharge signal, according to various embodiments. The system 160 includes at least one
25 sensor 142 and at least one detector 144 coupled to the at least one sensor 142, which may be similar to the embodiment as described in the context of FIG. 1C. The at least one sensor 142 may be a partial discharge sensor.

[0064] The system 160 further includes a data acquisition circuit 162 configured to convert the electrical signal from the at least one sensor 142 into a digital signal. The
30 system 160 may further include a processing device 164 configured to process the digital signal.

5 [0065] In various embodiments, the at least one sensor 142 may include a plurality of sensors, and wherein each of the plurality of sensors is configured to receive a respective partial discharge signal and convert the respective received partial discharge signal into a respective optical signal. The respective wavelength of the respective optical signal may be the same or different.

[0066] In various embodiments, the at least one detector 144 may include a plurality of detectors, and wherein each of the plurality of detectors is configured to detect the respective optical signal and convert the respective optical signal into a respective electrical signal.

10 [0067] In various embodiments, the coupling 146 may be an optical cable including a plurality of optical fibers, wherein a respective optical fiber of the plurality of optical fibers is configured to couple a respective detector of the plurality of detectors and a respective sensor of the plurality of sensors.

15 [0068] The system 160 may include an optical switch 170 coupled to the plurality of sensors. In such embodiments, the respective wavelength of the respective optical signal may be the same or different. The coupling 146 may be an optical fiber.

[0069] The system 160 may include at least one coupler 172 configured to combine the respective optical signal, and a demultiplexer 174 configured to receive and demultiplex the combined optical signal. In such embodiments, the respective wavelength of the
20 respective optical signal may be different. The coupling 146 may be an optical fiber.

[0070] In various embodiments, the at least one coupler 172 may include a plurality of couplers.

[0071] In various embodiments, the at least one coupler 172 may be a 1×2 coupler configured to combine two respective optical signals into the combined signal. The 1×2
25 coupler may have a coupling ratio of 10/90, 20/80, 30/70, 40/60 or 50/50.

[0072] In embodiments where the at least one coupler 172 is a 1×2 coupler and the at least one coupler 172 includes a plurality of couplers, the number of the plurality of couplers is one less than the number of the plurality of sensors.

30 [0073] The system 160 may include a multiplexer 176 configured to multiplex the respective optical signal, and a demultiplexer 178 configured to receive and demultiplex

the multiplexed optical signal. In such embodiments, the respective wavelength of the respective optical signal may be different. The coupling 146 may be an optical fiber.

[0074] FIG. 2A shows a flow chart illustrating a method 200 of forming a sensor, according to various embodiments. The sensor may be a partial discharge sensor.

5 [0075] At 202, an antenna configured to receive a partial discharge signal is provided.

[0076] At 204, a vertical-cavity surface-emitting laser is coupled to the antenna, wherein the vertical-cavity surface-emitting laser is configured to convert the received partial discharge signal into an optical signal.

10 [0077] In various embodiments, the vertical-cavity surface-emitting laser is coupled to the antenna by integrating the vertical-cavity surface-emitting laser in the antenna or coupling via an electrical interconnection, such as a radio frequency (RF) cable.

[0078] In various embodiments of the method 200, the RF cable is coupled to the vertical-cavity surface-emitting laser via an SMA connector or a BNC connector connected to an anode and a cathode of the vertical-cavity surface-emitting laser.

15 [0079] The method 200 may further include coupling a biasing circuit to the vertical-cavity surface-emitting laser. The method 200 may further include coupling an amplifying circuit to the vertical-cavity surface-emitting laser, where the amplifying circuit may be used to amplify the signal from the antenna (e.g. the partial discharge signal received by the antenna).

20 [0080] The method 200 may further include coupling an optical waveguide to the vertical-cavity surface-emitting laser, the optical waveguide configured to transmit the optical signal. The optical waveguide may be an optical fiber.

[0081] The method 200 may further include coupling a second antenna to the vertical-cavity surface-emitting laser.

25 [0082] FIG. 2B shows a flow chart illustrating a method 220 of forming a system for detecting a partial discharge signal, according to various embodiments.

[0083] At 222, at least one sensor is formed. In various embodiments, the at least one sensor may be formed based on the method described in the context of method 200. The at least one sensor may be a partial discharge sensor.

[0084] At 224, at least one detector is coupled to the at least one sensor, wherein the at least one detector is configured to detect the optical signal from the at least one sensor and convert the optical signal into an electrical signal.

5 [0085] The method 220 may further include providing a data acquisition circuit configured to convert the electrical signal from the at least one sensor into a digital signal.

[0086] The method 220 may further include providing a processing device configured to process the digital signal.

10 [0087] In various embodiments of the method 220, forming the at least one sensor may include forming a plurality of sensors, and wherein each of the plurality of sensors is configured to receive a respective partial discharge signal and convert the respective received partial discharge signal into a respective optical signal. The respective wavelength of the respective optical signal may be the same or different.

15 [0088] In various embodiments of the method 220, coupling the at least one detector comprises coupling a plurality of detectors, and wherein each of the plurality of detectors is configured to detect the respective optical signal and convert the respective optical signal into a respective electrical signal.

20 [0089] The method 220 may include providing an optical cable comprising a plurality of optical fibers, and coupling a respective optical fiber of the plurality of optical fibers to a respective detector of the plurality of detectors and a respective sensor of the plurality of sensors.

25 [0090] The method 220 may include coupling an optical switch to the plurality of sensors. In such embodiments, the respective wavelength of the respective optical signal may be the same or different. The optical switch may be coupled to the plurality of sensors via an optical fiber.

[0091] The method 220 may include providing at least one coupler configured to combine the respective optical signal, and providing a demultiplexer configured to receive and demultiplex the combined optical signal. In such embodiments, the respective wavelength of the respective optical signal may be different. The at least one coupler may
30 be coupled to the demultiplexer via an optical fiber.

[0092] In various embodiments, at least one coupler may include a plurality of couplers.

[0093] In various embodiments, the at least one coupler may be a 1×2 coupler configured to combine two respective optical signals into the combined signal. The 1×2 coupler may have a coupling ratio of 10/90, 20/80, 30/70, 40/60 or 50/50.

[0094] In embodiments where the at least one coupler is a 1×2 coupler and a plurality of couplers are provided, the number of the plurality of couplers is one less than the number of the plurality of sensors.

[0095] The method 220 may include providing a multiplexer configured to multiplex the respective optical signal, and providing a demultiplexer configured to receive and demultiplex the multiplexed optical signal. In such embodiments, the respective wavelength of the respective optical signal may be different. The multiplexer may be coupled to the demultiplexer via an optical fiber.

[0096] FIG. 2C shows a flow chart illustrating a method 240 of detecting a partial discharge signal, according to various embodiments.

[0097] At 242, a partial discharge signal is received by an antenna.

[0098] At 244, the received partial discharge signal is converted into an optical signal by a vertical-cavity surface-emitting laser coupled to the antenna. In various embodiments, in between the antenna and the vertical cavity surface emitting laser, an amplifying circuit may be used to amplify the signal from the antenna (e.g. the partial discharge signal received by the antenna).

[0099] The method 240 may further include converting the optical signal into an electrical signal. The method 240 may further include converting the electrical signal into a digital signal. The method 240 may further include processing the digital signal.

[0100] In the context of various embodiments, the antenna (e.g. the antenna 102 in FIGS. 1A and 1B and/or the second antenna 128 in FIG. 1B) configured to receive the partial discharge signal may include a pair of antennas coupled in series, in order to provide a dual-band antenna or a broadband antenna.

[0101] In the context of various embodiments, the antenna may be operable in a frequency range of between about a few kHz to about 1 GHz, for example a range of between about 100 kHz to about 1 GHz, a range of between about 1 MHz to about 500 MHz, a range of between about 1 MHz to about 300 MHz, a range of between about 200 MHz to about 400 MHz, a range of between about 100 MHz to about 400 MHz or a

range of between about 100 MHz to about 800 MHz. However, it should be appreciated that other frequency ranges may be possible.

[0102] In the context of various embodiments, the optical signal converted by the vertical-cavity surface-emitting laser may have the same or different frequency (or
5 correspondingly the same or different wavelength) from that of the partial discharge signal received by the antenna.

[0103] In the context of various embodiments, the term “partial discharge signal” may mean a signal emitted as a result of the partial discharge, the signal emanating from the discharge site. The partial discharge signal may include energy that is emitted by the
10 partial discharge, for example electromagnetic emissions, for example in the form of radio waves.

[0104] In the context of various embodiments, the antenna may couple energy of an electromagnetic emission, for example radio waves, and generate an electrical signal (e.g. current).

15 [0105] In the context of various embodiments, the vertical-cavity surface-emitting laser (VCSEL) is a type of semiconductor laser diode which emits a laser beam or radiation in a direction perpendicular from a surface (e.g. a top surface or a bottom surface) of the VCSEL, contrary to conventional edge-emitting semiconductor lasers. In edge emitting semiconductor lasers, laser beam emission is from surfaces formed by cleaving the
20 individual chip out of a wafer.

[0106] In various embodiments, the VCSEL includes a laser resonator having two distributed Bragg reflector (DBR) mirrors (or reflectors) parallel to the wafer surface with an active region in between the DBR mirrors, where the active region includes one or more quantum wells for the laser light generation. Each of the planar DBR-mirrors
25 includes layers with alternating high and low refractive indices. One of the DBR mirrors is n-doped while the other is p-doped.

[0107] In the context of various embodiments, the vertical-cavity surface-emitting laser (VCSEL) may be of the embodiment as shown in FIG. 17.

30 [0108] In the context of various embodiments, a ‘circuit’ may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in

an embodiment, a 'circuit' may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g. a microprocessor (e.g. a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A 'circuit' may also be a processor executing software, e.g. any kind of computer program, e.g. a computer program using a virtual machine code such as e.g. Java. Any other kind of implementation of the respective functions which will be described in more detail below may also be understood as a 'circuit' in accordance with an alternative embodiment.

[0109] FIG. 3 shows a schematic view of a partial discharge sensor 300, according to various embodiments. The partial discharge sensor 300 includes an antenna 302 and a vertical-cavity surface-emitting laser (VCSEL) 304. The VCSEL 304 is coupled directly or connected directly to the antenna 302. In some embodiments, the VCSEL 304 may be integrated in or with the antenna 302.

[0110] The antenna 302 may be used to receive one or more partial discharge (PD) signals, while the VCSEL laser 304 may be used to convert the one or more PD signals into one or more optical signals.

[0111] The partial discharge sensor 300 further includes a biasing circuit 306 coupled to the VCSEL 302. The biasing circuit 306 may be coupled to the VCSEL 302 via electrical interconnections 310, e.g. wires. The biasing circuit 306 may provide biasing conditions, for example voltages and/or currents, to the VCSEL laser 304. The biasing circuit 306 may include a power supply. The partial discharge sensor 300 may further include an amplifying circuit (not shown) coupled to the VCSEL 304 for amplifying the signal from the antenna 302.

[0112] The partial discharge sensor 300 may further include an optical fiber 308 for propagation or transmission of the optical signal or signals.

[0113] FIG. 4 shows a schematic view of a partial discharge sensor 400, according to various embodiments. The partial discharge sensor 400 includes an antenna 402 and a vertical-cavity surface-emitting laser (VCSEL) 404. The VCSEL 404 is coupled or connected to the antenna 402 via an RF cable 406. In other words, the VCSEL 404 is coupled indirectly to the antenna 302.

[0114] The antenna 402 may include a SubMiniature version A (SMA) connector, a Bayonet Neill-Concelman (BNC) connector or any type of RF connector, for coupling to the RF cable 406. The VCSEL 404 may include an SMA connector, a BNC connector or any type of RF connector connected to the anode and the cathode of the VCSEL 404, the
5 connector being used for coupling to the RF cable 406.

[0115] The antenna 402 may be used to receive one or more partial discharge (PD) signals, while the VCSEL laser 404 may be used to convert the one or more PD signals into one or more optical signals.

[0116] The partial discharge sensor 400 further includes a biasing circuit 408 coupled to
10 the VCSEL 404. The biasing circuit 408 may be coupled to the VCSEL 404 via electrical interconnections 412, e.g. wires. The biasing circuit 408 may provide biasing conditions, for example voltages and/or currents, to the VCSEL laser 404. The biasing circuit 408 may include a power supply. The partial discharge sensor 400 may further include an amplifying circuit (not shown) coupled to the VCSEL 404, for example coupled between
15 the antenna 402 and the VCSEL 404, for amplifying the signal from the antenna 402.

[0117] The partial discharge sensor 400 may further include an optical fiber 410 for propagation or transmission of the optical signal or signals.

[0118] In various embodiments, the partial discharge sensor 400 provides flexibility in installation and application, as the antenna 402 and the VCSEL 404, with its associated
20 circuits and power supply, are separately provided.

[0119] FIG. 5 shows a schematic view of a partial discharge sensor 500, according to various embodiments. The partial discharge sensor 500 includes two antennas, e.g. a first antenna 502 and a second antenna 504, and a vertical-cavity surface-emitting laser (VCSEL) 506.

[0120] The VCSEL 506 is coupled or connected to the first antenna 502 via a first RF
25 cable 508 and also coupled or connected to the second antenna 504 via a second RF cable 510. Therefore, the VCSEL 506 is coupled indirectly to the first antenna 502 and the second antenna 504.

[0121] Each of the first antenna 502 and the second antenna 504 may include a
30 SubMiniature version A (SMA) connector, a Bayonet Neill-Concelman (BNC) connector or any type of RF connector, for coupling respectively to the first RF cable 508 and the

second RF cable 510. The VCSEL 506 may include an SMA connector, a BNC connector or any type of RF connector connected to the anode and the cathode of the VCSEL 506, the connector being used for coupling to the first RF cable 508 and the second RF cable 510.

5 **[0122]** The first antenna 502 and the second antenna 504 may be used to receive one or more partial discharge (PD) signals, while the VCSEL laser 506 may be used to convert the one or more PD signals into one or more optical signals. In addition, each of the first antenna 502 and the second antenna 504 may be positioned at two locations, either in the same vicinity or at different locations, to cover a larger sensing area.

10 **[0123]** The partial discharge sensor 500 further includes a biasing circuit 512 coupled to the VCSEL 506. The biasing circuit 512 may be coupled to the VCSEL 506 via electrical interconnections 514, e.g. wires. The biasing circuit 512 may provide biasing conditions, for example voltages and/or currents, to the VCSEL laser 506. The biasing circuit 512 may include a power supply. The partial discharge sensor 500 may further include an
15 amplifying circuit (not shown) coupled to the VCSEL 506, for example coupled between the first antenna 502 and the second antenna 504, and the VCSEL 506, for amplifying the signals from the first antenna 502 and the second antenna 504.

[0124] The partial discharge sensor 500 may further include an optical fiber 516 for propagation or transmission of the optical signal or signals.

20 **[0125]** In various embodiments, the partial discharge sensor 500 provides flexibility in installation and application, as the first antenna 502, the second antenna 504 and the VCSEL 506, with its associated circuits and power supply, are separately provided.

[0126] FIG. 6A shows a schematic view of an antenna 600, according to various embodiments. The antenna 600 includes a pair of elements 602a, 602b, arranged as
25 mirror images of each other about the central axis, as represented by 604. Each of the elements 602a, 602b, may be arranged in the form of a continuous rectangular serpentine line, as shown in FIG. 6A. It should be appreciated that the size and dimensions of the elements 602a, 602b, and therefore also the size and dimensions of the antenna 600, may be varied for different ranges of frequencies of the partial discharge emission or partial
30 discharge signal. In other words, the size and dimensions of the antenna 600 may be varied to detect partial discharge emission or partial discharge signal of different ranges

of frequencies. Therefore, any size of the antenna 600 may be provided depending on the frequencies of the partial discharge emission to be received by the antenna 600.

[0127] FIG. 6B shows a schematic view of a dual-band antenna (or a broadband antenna) 620, according to various embodiments. The dual-band antenna 620 may be used to broaden the frequency measurement range of the partial discharge emission. The dual-band antenna 620 includes a pair of antennas 622, 624, coupled in series, end-to-end. Each of the pair of antennas 622, 624, may be of the embodiment of FIG. 6A.

[0128] FIG. 7 shows a schematic view of a system 700 for detecting a partial discharge signal, according to various embodiments. The system 700 includes a partial discharge sensor (PD sensor) 702, which may be, for example, any one of the embodiments of FIGS. 3-5.

[0129] The system 700 further includes an optical detector or detector module 704, a data acquisition circuit (DAQ) 706 and a computer 708. The DAQ 706 is coupled to the detector module 704 while the computer 708 is coupled to the DAQ 706.

[0130] In various embodiments, the system 700 includes a single optical fiber 710 for coupling between the partial discharge sensor 702 and the detector module 704.

[0131] In various embodiments, the optical fiber 710 may be the same optical fiber of the partial discharge sensor 702. As an example and not limitation, where the partial discharge sensor 702 is based on the partial discharge sensor 300 with the optical fiber 308 of FIG. 3, the optical fiber 710 of the system 700 may be the optical fiber 308.

[0132] In various embodiments, the optical fiber 710 may be a separate optical fiber from the optical fiber of the partial discharge sensor 702. For example, in embodiments where an optical fiber with a greater length is required in order to extend the operating length of the partial discharge sensor 702, the optical fiber 710 may be a separate optical fiber, which may be coupled (e.g. fusion spliced) to the optical fiber of the partial discharge sensor 702.

[0133] In the system 700, the optical signal from the partial discharge sensor 702 is transmitted via the optical fiber 710 to the detector module 704, where the optical signal is converted to an electrical signal by the detector module 704. The electrical signal may then be converted into a digital signal by the DAQ 706 and the signal or data acquired by the DAQ 706. Signal processing of the digital signal may then be performed by the

computer 708, for example the signal is manipulated and/or analysed, and then results and/or reporting is generated by the computer 708.

[0134] FIG. 8 shows a schematic view of a system 800 for detecting a partial discharge signal, according to various embodiments. The system 800 includes an array of partial discharge (PD) sensors 801, for example n PD sensors including a first PD sensor (PD sensor 1) 802a, a second PD sensor (PD sensor 2) 802b, to an n -th PD sensor (PD sensor n) 802c. In various embodiments, the number of PD sensors, i.e. the integer n , may be 3, 4, 5, 6, 7, 8 or any higher number, depending on requirements and applications of the system 800.

[0135] Each PD sensor of the array of sensors 801, for example the first PD sensor 802a, the second PD sensor 802b and the n -th PD sensor 802c, may be, for example, any one of the embodiments of FIGS. 3-5. In various embodiments, all or some of the PD sensors of the array of sensors 801 may be of the same or different embodiments of FIGS. 3-5.

[0136] Each PD sensor of the array of sensors 801, for example the first PD sensor 802a, the second PD sensor 802b and the n -th PD sensor 802c, may operate at the same wavelength or different wavelengths.

[0137] Each PD sensor may be coupled to a respective optical fiber. As shown in FIG. 8, the first PD sensor 802a, the second PD sensor 802b and the n -th PD sensor 802c are coupled respectively to the optical fiber 804a, 804b, 804c. In various embodiments, the respective optical fiber 804a, 804b, 804c, may be the respective fiber being part of the respective first PD sensor 802a, second PD sensor 802b and n -th PD sensor 802c, or the respective optical fiber 804a, 804b, 804c, may be separate fibers respectively coupled (e.g. fused) to the respective fiber of the respective first PD sensor 802a, second PD sensor 802b and n -th PD sensor 802c.

[0138] The system 800 further includes a detector array 806, a data acquisition circuit (DAQ) 808 and a computer 810. The DAQ 808 is coupled to the detector array 806 while the computer 810 is coupled to the DAQ 808.

[0139] The detector array 806 may include a plurality of detectors. It should be appreciated that the detector array 806 may include any number of detectors, the number of which is at least the same as the number of sensors in the sensor array 801. For

example, based on the embodiment of FIG. 8, the detector array 806 may have n detectors.

[0140] The system 800 further includes an optical fiber cable 812 with multi-individual fibers or a plurality of optical fibers for coupling or connecting the PD sensor array 801 and the detector array 806. The optical fiber cable 812 includes, for example a first optical fiber 814a, a second optical fiber 814b and a third optical fiber 814c, respectively coupled to the optical fibers 804a, 804b, 804c. Therefore, each sensor of the sensor array 801 is coupled to the detector array 806 via an individual fiber. At the detector array 806, each of the optical fibers 814a, 814b, 814c, may in turn be coupled to an individual detector.

[0141] For clarity and illustration purposes, only three individual optical fibers of the optical fiber cable 812 are shown. However, it should be appreciated that the optical fiber cable 812 may include any number of individual optical fibers, the number of which is at least the same as the number of sensors in the sensor array 801.

[0142] In the system 800, the respective optical signal from the first PD sensor 802a, the second PD sensor 802b and the n -th PD sensor 802c is transmitted via the respective optical fibers 804a, 804b, 804c, and then the respective optical fibers 814a, 814b, 814c, of the optical fiber cable 812, to the detector array 806, where the respective optical signal is converted to a respective electrical signal by the respective detector in the detector array 806. The respective electrical signal may then be converted into a respective digital signal by the DAQ 808 and the respective signal or data acquired by the DAQ 808. Signal processing may then be performed by the computer 810, for example the respective signal is manipulated, analysed and/or combined, and then results and/or reporting is generated by the computer 810.

[0143] The system 800 may be used to detect one or more partial discharge signals from an equipment (e.g. a power equipment). In various embodiments, each sensor of the sensor array 801 may be positioned at a single location or different locations on the equipment to detect partial discharge signals from the respective location or locations. In various embodiments, more than one sensor of the sensor array 801 may be positioned at a particular location of the different locations on the equipment where detection of partial discharge signals is to be carried out.

[0144] FIG. 9 shows a schematic view of a system 900 for detecting a partial discharge signal, according to various embodiments. The system 900 includes an array of partial discharge (PD) sensors 902, for example n PD sensors including a first PD sensor (PD sensor 1) 904a, a second PD sensor (PD sensor 2) 904b, to an n -th PD sensor (PD sensor n) 904c. In various embodiments, the number of PD sensors, i.e. the integer n , may be 3, 4, 5, 6, 7, 8 or any higher number, depending on requirements and applications of the system 900.

[0145] Each PD sensor of the array of sensors 902, for example the first PD sensor 904a, the second PD sensor 904b and the n -th PD sensor 904c, may be, for example, any one of the embodiments of FIGS. 3-5. In various embodiments, all or some of the PD sensors of the array of sensors 902 may be of the same or different embodiments of FIGS. 3-5.

[0146] Each PD sensor of the array of sensors 902, for example the first PD sensor 904a, the second PD sensor 904b and the n -th PD sensor 904c, may operate at different wavelengths.

[0147] Each PD sensor may be coupled to a respective optical fiber. As shown in FIG. 9, the first PD sensor 904a, the second PD sensor 904b and the n -th PD sensor 904c are coupled respectively to the optical fiber 906a, 906b, 906c. In various embodiments, the respective optical fiber 906a, 906b, 906c, may be the respective fiber being part of the respective first PD sensor 904a, second PD sensor 904b and n -th PD sensor 904c, or the respective optical fiber 906a, 906b, 906c, may be separate fibers respectively coupled (e.g. fused) to the respective fiber of the respective first PD sensor 904a, second PD sensor 904b and n -th PD sensor 904c.

[0148] The system 900 may include one or more fiber couplers, for example tap couplers. As shown in FIG. 9, the system 900 includes a number of couplers, for example a first 1×2 coupler 908a and a second 1×2 coupler 908b, which are used to combine optical signals from the sensor array 902 onto a single optical fiber 910. For example, the respective optical signal from the second PD sensor 904b and the n -th PD sensor 904c may be combined via the first 1×2 coupler 908a to produce an intermediate combined signal which is then combined with the optical signal from the first PD sensor 904a via the second 1×2 coupler 908b to produce a final combined signal for transmission on the optical fiber 910. In various embodiments, coupling between the first 1×2 coupler 908a

and the second 1×2 coupler 908b may be, for example, by an optical fiber 912. The optical fiber 912 may be part of the first 1×2 coupler 908a and/or the second 1×2 coupler 908b.

5 [0149] In the context of various embodiments, a 1×2 coupler means a coupler having two inputs and an output, for example a coupler which may receive two input optical signals and combine the two optical signals to produce a single output signal.

[0150] Each of the first 1×2 coupler 908a and the second 1×2 coupler 908b may have a coupling ratio of about 10/90, such that the output signal may include 10% of a first input optical signal and 90% of a second input optical signal. However, it should be
10 appreciated that each of the first 1×2 coupler 908a and the second 1×2 coupler 908b may have other coupling ratios, for example about 20/80, about 30/70, about 40/60, about 50/50 or about 60/40. In various embodiments, each of the first 1×2 coupler 908a and the second 1×2 coupler 908b may have the same coupling ratio or different coupling ratios.

[0151] For clarity and illustration purposes, only two couplers are shown. However, it
15 should be appreciated that any number of couplers may be provided depending on the number of inputs of each coupler and the number of sensors. For example, where each coupler is a 1×2 coupler, the number of couplers is one less than the number of sensors in the sensor array 902. For example, based on the embodiment of FIG. 9, the number of 1×2 couplers is $(n-1)$.

20 [0152] While 1×2 couplers are illustrated in the embodiment of FIG. 9, in various embodiments, the system 900 may incorporate other configurations of couplers, for example one or more 1×3 couplers, one or more 1×4 couplers or one or more 2×2 couplers. In various embodiments, different configurations of couplers may be used in the system 900.

25 [0153] The system 900 may further include a wavelength-division multiplexing (WDM) demultiplexer 914 coupled to the optical fiber 910, a detector array 916, a data acquisition circuit (DAQ) 918 and a computer 920. The detector array 916 is coupled to the demultiplexer 914, the DAQ 918 is coupled to the detector array 916 while the computer 920 is coupled to the DAQ 918.

[0154] The WDM demultiplexer 914 may include a plurality of channels, where the WDM demultiplexer 914 is used to demultiplex or separate the combined signal transmitted via the optical fiber 910 into respective optical signals of different wavelengths. Each of the separated optical signal is then transmitted, for example via an individual optical fiber, to a detector in the detector array 916.

[0155] It should be appreciated that the WDM demultiplexer 914 may include any number of channels, the number of which is at least the same as the number of sensors in the sensor array 902. For example, based on the embodiment of FIG. 9, the WDM demultiplexer 914 may have n channels.

[0156] It should be appreciated that the detector array 916 may include any number of detectors, the number of which is at least the same as the number of sensors in the sensor array 902. For example, based on the embodiment of FIG. 9, the detector array 916 may have n detectors.

[0157] At the detector array 916, the respective separated optical signal is converted to a respective electrical signal by the respective detector. The respective electrical signal may then be converted into a respective digital signal by the DAQ 918 and the respective signal or data is acquired by the DAQ 918. Signal processing may then be performed by the computer 920, for example the respective signal is manipulated, analysed and/or combined, and then results and/or reporting is generated by the computer 920.

[0158] The system 900 may be used to detect one or more partial discharge signals from an equipment (e.g. a power equipment). In various embodiments, each of the sensors of the sensor array 902 may be positioned at a single location or different locations on the equipment to detect partial discharge signals from the respective location or locations. In various embodiments, more than one sensor of the sensor array 902 may be positioned at a particular location of the different locations on the equipment where detection of partial discharge signals is to be carried out.

[0159] FIG. 10 shows a schematic view of a system 1000 for detecting a partial discharge signal, according to various embodiments. The system 1000 includes an array of partial discharge (PD) sensors 1002, for example n PD sensors including a first PD sensor (PD sensor 1) 1004a, a second PD sensor (PD sensor 2) 1004b, to an n -th PD sensor (PD sensor n) 1004c. In various embodiments, the number of PD sensors, i.e. the integer n ,

may be 3, 4, 5, 6, 7, 8 or any higher number, depending on requirements and applications of the system 1000.

[0160] Each PD sensor of the array of sensors 1002, for example the first PD sensor 1004a, the second PD sensor 1004b and the n -th PD sensor 1004c, may be, for example, any one of the embodiments of FIGS. 3-5. In various embodiments, all or some of the PD sensors of the array of sensors 1002 may be of the same or different embodiments of FIGS. 3-5.

[0161] Each PD sensor of the array of sensors 1002, for example the first PD sensor 1004a, the second PD sensor 1004b and the n -th PD sensor 1004c, may operate at different wavelengths.

[0162] Each PD sensor may be coupled to a respective optical fiber. As shown in FIG. 10, the first PD sensor 1004a, the second PD sensor 1004b and the n -th PD sensor 1004c are coupled respectively to the optical fiber 1006a, 1006b, 1006c. In various embodiments, the respective optical fiber 1006a, 1006b, 1006c, may be the respective fiber being part of the respective first PD sensor 1004a, second PD sensor 1004b and n -th PD sensor 1004c, or the respective optical fiber 1006a, 1006b, 1006c, may be separate fibers respectively coupled (e.g. fused) to the respective fiber of the respective first PD sensor 1004a, second PD sensor 1004b and n -th PD sensor 1004c.

[0163] The system 1000 may include a wavelength-division multiplexing (WDM) multiplexer 1008, which is used to combine the optical signals from the sensor array 1002 for transmission on a single optical fiber 1010. For example, the respective optical signal from the first PD sensor 1004a, the second PD sensor 1004b and the n -th PD sensor 1004c may be multiplexed or combined by the WDM multiplexer 1008 to produce a combined or multiplexed optical signal for transmission on the optical fiber 1010.

[0164] The WDM multiplexer 1008 may include a plurality of channels, where any number of channels may be provided, the number of which is at least the same as the number of sensors in the sensor array 1002. For example, based on the embodiment of FIG. 10, the WDM multiplexer 1008 may have n channels.

[0165] The system 1000 may further include a wavelength-division multiplexing (WDM) demultiplexer 1012, a detector array 1014, a data acquisition circuit (DAQ) 1016 and a

computer 1018. The optical fiber 1010 provides coupling between the WDM multiplexer 1008 and the WDM demultiplexer 1012.

[0166] In various embodiments, the detector array 1014 is coupled to the demultiplexer 1012, the DAQ 1016 is coupled to the detector array 1014 while the
5 computer 1018 is coupled to the DAQ 1016.

[0167] The WDM demultiplexer 1012 may include a plurality of channels, where the WDM demultiplexer 1012 is used to demultiplex or separate the combined signal transmitted via the optical fiber 1010 into respective optical signals of different wavelengths. Each of the separated optical signal is then transmitted, for example via an
10 individual optical fiber, to a detector in the detector array 1014.

[0168] It should be appreciated that the WDM demultiplexer 1012 may include any number of channels, the number of which is at least the same as the number of sensors in the sensor array 1002. For example, based on the embodiment of FIG. 10, the WDM demultiplexer 1012 may have n channels.

15 [0169] It should be appreciated that the detector array 1014 may include any number of detectors, the number of which is at least the same as the number of sensors in the sensor array 1002. For example, based on the embodiment of FIG. 10, the detector array 1014 may have n detectors.

[0170] At the detector array 1014, the respective separated optical signal is converted to a
20 respective electrical signal by the respective detector. The respective electrical signal may then be converted into a respective digital signal by the DAQ 1016 and the respective signal or data acquired by the DAQ 1016. Signal processing may then be performed by the computer 1018, for example the respective signal is manipulated, analysed and/or combined, and then results and/or reporting is generated by the computer 1018.

25 [0171] The system 1000 may be used to detect one or more partial discharge signals from an equipment (e.g. a power equipment). In various embodiments, each of the sensors of the sensor array 1002 may be positioned at a single location or different locations on the equipment to detect partial discharge signals from the respective location or locations. In various embodiments, more than one sensor of the sensor array 1002 may be positioned
30 at a particular location of the different locations on the equipment where detection of partial discharge signals is to be carried out.

[0172] FIG. 11 shows a schematic view of a system 1100 for detecting a partial discharge signal, according to various embodiments. The system 1100 includes an array of partial discharge (PD) sensors 1102, for example n PD sensors including a first PD sensor (PD sensor 1) 1104a, a second PD sensor (PD sensor 2) 1104b, a third PD sensor (PD sensor 3) 1104c, to an n -th PD sensor (PD sensor n) 1104d. In various embodiments, the number of PD sensors, i.e. the integer n , may be 4, 5, 6, 7, 8 or any higher number, depending on requirements and applications of the system 1100.

[0173] Each PD sensor of the array of sensors 1102, for example the first PD sensor 1104a, the second PD sensor 1104b, the third PD sensor 1104c and the n -th PD sensor 1104d, may be, for example, any one of the embodiments of FIGS. 3-5. In various embodiments, all or some of the PD sensors of the array of sensors 1102 may be of the same or different embodiments of FIGS. 3-5.

[0174] Each PD sensor of the array of sensors 1102, for example the first PD sensor 1104a, the second PD sensor 1104b, the third PD sensor 1104c and the n -th PD sensor 1104d, may operate at the same wavelength or different wavelengths.

[0175] Each PD sensor may be coupled to a respective optical fiber. As shown in FIG. 11, the first PD sensor 1104a, the second PD sensor 1104b, the third PD sensor 1104c and the n -th PD sensor 1104d are coupled respectively to the optical fiber 1106a, 1106b, 1106c, 1106d. In various embodiments, the respective optical fiber 1106a, 1106b, 1106c, 1106d, may be the respective fiber being part of the respective first PD sensor 1104a, second PD sensor 1104b, third PD sensor 1104c and n -th PD sensor 1104d, or the respective optical fiber 1106a, 1106b, 1106c, 1106d, may be separate fibers respectively coupled (e.g. fused) to the respective fiber of the respective first PD sensor 1104a, second PD sensor 1104b, third PD sensor 1104c and n -th PD sensor 1104d.

[0176] The system 1100 may include a $(1 \times n)$ optical switch 1108, which is used to transmit any one of the respective optical signal from the sensor array 1002, at any one time, for transmission onto an optical fiber 1110 to be received by an optical detector or a detector module 1112. Therefore, the optical switch 1108 connects the sensor array 1002 and the detector module 1112. The optical fiber 1110 may be part of the optical switch 1108.

[0177] In the context of various embodiments, a $1 \times n$ optical switch means an optical switch having n inputs and an output, for example an optical switch which may switch among the n input optical signals and transmit one of the n input optical signals as an output signal.

5 [0178] As an example, the optical switch 1108 may select the optical signal from either the first PD sensor 1104a, the second PD sensor 1104b, the third PD sensor 1104c or the n -th PD sensor 1104d for transmission on the optical fiber 1110, at any one time. In other words, the optical switch 1108 provides coupling of the detector module 1112 and either one of the first PD sensor 1104a, the second PD sensor 1104b, the third PD sensor 1104c
10 or the n -th PD sensor 1104d, such that the detector module 1112 receives one optical signal at any one time.

[0179] While a $1 \times n$ optical switch is illustrated in the embodiment of FIG. 11, in various embodiments, the system 1100 may incorporate another configuration of the optical switch, for example a $1 \times N$ optical switch. In various embodiments, N is at least the same
15 as the number of sensors in the sensor array 1102 (i.e. $N = n$ for the embodiment of FIG. 11). In further embodiments, N may be $n+1$, $n+2$, $n+3$ or any higher number.

[0180] The system 1100 further includes a data acquisition circuit (DAQ) 1114 and a computer 1116. The DAQ 1114 is coupled to the detector module 1112 while the computer 1116 is coupled to the DAQ 1114.

20 [0181] In the system 1100, the optical signal received by the detector module 1112, is converted to an electrical signal by the detector module 1112. The electrical signal may then be converted into a digital signal by the DAQ 1114 and the signal or data acquired by the DAQ 1114. Signal processing of the digital signal may then be performed by the computer 1116, for example the signal is manipulated and/or analysed, and then results
25 and/or reporting is generated by the computer 1116.

[0182] The system 1100 may be used to detect one or more partial discharge signals from an equipment (e.g. a power equipment). In various embodiments, each of the sensors of the sensor array 1102 may be positioned at a single location or different locations on the equipment to detect partial discharge signals from the respective location or locations. In
30 various embodiments, more than one sensor of the sensor array 1102 may be positioned

at a particular location of the different locations on the equipment where detection of partial discharge signals is to be carried out.

[0183] FIG. 12 shows photographs 1200, 1202, of a partial discharge (PD) sensor or a PD sensor head 1204 of various embodiments.

5 [0184] FIG. 13 shows a partial discharge (PD) signal 1300, according to various embodiments, as observed on a spectrum analyzer. The partial discharge signal 1300 is a spectrum of a detected partial discharge generated from a PD kit, for a surface case where the partial discharge occurs on a material surface, at about 5 kV polarization. The distance between the partial discharge sensor and the PD source is about 5 inches (i.e.
10 about 0.127 m or about 12.7 cm). FIG. 13 shows that the PD frequency emission is concentrated within the spectrum from about 25 MHz to about 400 MHz, the range being represented as 1302.

[0185] FIG. 14 shows a plot 1400 of a partial discharge (PD) signal 1402, according to various embodiments. The partial discharge signal 1402 is a partial discharge frequency
15 emission detected by a partial discharge sensor of various embodiments, for example the embodiment of FIG. 12, and being designed for operation in the range of between about 100 MHz to about 500 MHz. The partial discharge signal 1402 is a spectrum of a detected partial discharge generated from a PD kit, for a cavity case where the partial discharge occurs within a material, at about 5 kV polarization. The distance between the
20 partial discharge sensor and the PD source is about 7 inches (i.e. about 0.178 m or about 17.8 cm).

[0186] In various embodiments, in the time domain, the partial discharge signals generated at about 3 kV polarization may be detected and measured, and the results are shown in FIG. 15. FIG. 15 shows a plot 1500 of a partial discharge signal 1502 in time
25 domain, according to various embodiments. For comparison purposes, a noise signal 1504 is also included. As shown in FIG. 15, the corresponding peak-to-peak value of the partial discharge signal or waveform 1502 is about 80 mV.

[0187] FIG. 16 shows a photograph 1600 of a system for detecting partial discharge signals, according to various embodiments. The system includes four PD sensor heads
30 1602a, 1602b, 1602c, 1602d, which as shown in the photograph 1600, are attached at different locations on the panels of a high voltage (HV) equipment 1604. Each of the four

PD sensor heads 1602a, 1602b, 1602c, 1602d, may be a PD sensor of various embodiments, or for example the PD sensor head 1204 as shown in FIG. 12. Each of the four PD sensor heads 1602a, 1602b, 1602c, 1602d, may have the same or different configurations.

5 [0188] FIG. 17 shows a schematic perspective view of a vertical-cavity surface-emitting laser (VCSEL) 1700, according to various embodiments. The VCSEL 1700 includes a laser resonator having two distributed Bragg reflector (DBR) mirrors (or reflectors), e.g. an upper Bragg reflector 1702 and a lower Bragg reflector 1704. The VCSEL 1700 further includes an active region 1706 in between the upper Bragg reflector 1702 and the
10 lower Bragg reflector 1704, where the active region 1706 includes one or more quantum wells for the laser light generation. Each of the planar upper Bragg reflector 1702 and the planar lower Bragg reflector 1704 includes layers with alternating high and low refractive indices. As an example and not limitations, the upper Bragg reflector 1702 may be p-doped (e.g. p-AlGaAs/GaAs) while the lower Bragg reflector 1704 may be n-doped (e.g.
15 n-AlGaAs/GaAs). The upper Bragg reflector 1702 and the lower Bragg reflector 1704 may have the same or different periods.

[0189] The VCSEL 1700 may be provided on an n-doped substrate 1708 (e.g. n-GaAs substrate). The VCSEL 1700 further includes two metal contacts, e.g. an upper metal contact 1710 and a lower metal contact 1712. The upper metal contact 1710 may be p-
20 doped (e.g. p⁺GaAs) while the lower metal contact 1712 may be n-doped (e.g. n⁺GaAs).

[0190] The VCSEL 1700 further includes a cavity 1714 for top emission of the laser radiation, as represented by the arrow 1716.

[0191] The VCSEL 1700 may be used in the PD sensors of various embodiments. However, it should be appreciated that VCSELs of other configurations and/or materials
25 may also be provided.

[0192] In various embodiments, VCSELs provide enhanced sensitivity in the detection of partial discharge signal or signals, compared to Fabry-Perot laser or other types of lasers. Furthermore, VCSEL is a widely available laser in the market and provides a cheaper alternative an to electro-optic (EO) modulator for the detection of PD signals where EO
30 modulator is used to convert the PD signals to optical signals.

[0193] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is
5 thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A sensor comprising:
 - an antenna configured to receive a partial discharge signal; and
 - 5 a vertical-cavity surface-emitting laser coupled to the antenna, wherein the vertical-cavity surface-emitting laser is configured to convert the received partial discharge signal into an optical signal,
 - wherein the antenna comprises a pair of antennas coupled in series to each other, each of the pair of antennas comprising a pair of elements arranged as mirror images of
 - 10 each other about a central axis of the pair of elements, each element of the pair of elements comprising a continuous rectangular serpentine line, and
 - wherein each of the pair of antennas is dimensioned differently from the other of the pair of antennas to receive a partial discharge signal of a frequency different from a partial discharge signal to be received by the other of the pair of antennas.
- 15 2. The sensor as claimed in claim 1, wherein the vertical-cavity surface-emitting laser is integrated in the antenna.
3. The sensor as claimed in claim 1, wherein the vertical-cavity surface-emitting
- 20 laser is coupled to the antenna via an electrical interconnection.
4. The sensor as claimed in claim 3, wherein the electrical interconnection is an RF cable.
- 25 5. The sensor as claimed in claim 4, wherein the vertical-cavity surface-emitting laser comprises an SMA connector or a BNC connector coupled to an anode and a cathode of the vertical-cavity surface-emitting laser for coupling to the RF cable.
6. The sensor as claimed in any one of claims 1 to 5, further comprising a biasing
- 30 circuit coupled to the vertical-cavity surface-emitting laser.

7. The sensor as claimed in any one of claims 1 to 6, further comprising an amplifying circuit coupled to the vertical-cavity surface-emitting laser.

8. The sensor as claimed in any one of claims 1 to 7, further comprising an optical waveguide coupled to the vertical-cavity surface-emitting laser, the optical waveguide configured to transmit the optical signal.

9. The sensor as claimed in claim 8, wherein the optical waveguide is an optical fiber.

10. The sensor as claimed in any one of claims 1 to 9, wherein the optical signal has a different frequency from that of the partial discharge signal.

11. The sensor as claimed in any one of claims 1 to 10, wherein the antenna is operable in a frequency range of between about 100 kHz to about 1 GHz.

12. The sensor as claimed in any one of claims 1 to 11, further comprising a second antenna coupled to the vertical-cavity surface-emitting laser.

13. A system for detecting a partial discharge signal, the system comprising:
at least one sensor as claimed in any one of claims 1 to 12; and
at least one detector coupled to the at least one sensor, wherein the at least one detector is configured to detect the optical signal from the at least one sensor and convert the optical signal into an electrical signal.

14. The system as claimed in claim 13, further comprising a data acquisition circuit configured to convert the electrical signal from the at least one sensor into a digital signal.

15. The system as claimed in claim 14, further comprising a processing device configured to process the digital signal.

16. The system as claimed in any one of claims 13 to 15, wherein the at least one sensor comprises a plurality of sensors, and wherein each of the plurality of sensors is configured to receive a respective partial discharge signal and convert the respective received partial discharge signal into a respective optical signal.

17. The system as claimed in claim 16, wherein the at least one detector comprises a plurality of detectors, and wherein each of the plurality of detectors is configured to detect the respective optical signal and convert the respective optical signal into a respective electrical signal.

18. The system as claimed in claim 17, further comprising an optical cable comprising a plurality of optical fibers, wherein a respective optical fiber of the plurality of optical fibers is configured to couple a respective detector of the plurality of detectors and a respective sensor of the plurality of sensors.

19. The system as claimed in any one of claims 16 to 18, further comprising an optical switch coupled to the plurality of sensors.

20. The system as claimed in any one of claims 16 to 19, wherein a respective wavelength of the respective optical signal is different.

21. The system as claimed in claim 20, further comprising:
at least one coupler configured to combine the respective optical signal; and
a demultiplexer configured to receive and demultiplex the combined optical signal.

22. The system as claimed in claim 21, wherein the at least one coupler is a 1×2 coupler configured to combine two respective optical signals into the combined signal.

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23. The system as claimed in claim 22, wherein the 1×2 coupler has a coupling ratio selected from a group consisting of 10/90, 20/80, 30/70, 40/60 and 50/50.

24. The system as claimed in claim 22 or 23, wherein the at least one coupler comprises a plurality of couplers, wherein the number of the plurality of couplers is one less than the number of the plurality of sensors.

25. The system as claimed in any one of claims 21 to 24, wherein the at least one coupler is coupled to the demultiplexer via an optical fiber.

26. The system as claimed in claim 20, further comprising:
a multiplexer configured to multiplex the respective optical signal; and
a demultiplexer configured to receive and demultiplex the multiplexed optical signal.

27. The system as claimed in claim 26, wherein the multiplexer is coupled to the demultiplexer via an optical fiber.

28. A method of manufacturing a sensor, the method comprising:
providing an antenna configured to receive a partial discharge signal; and
coupling a vertical-cavity surface-emitting laser to the antenna, wherein the vertical-cavity surface-emitting laser is configured to convert the received partial discharge signal into an optical signal,

wherein providing the antenna comprises providing a pair of antennas coupled in series to each other, each of the pair of antennas comprising a pair of elements arranged as mirror images of each other about a central axis of the pair of elements, each element of the pair of elements comprising a continuous rectangular serpentine line, and

wherein each of the pair of antennas is dimensioned differently from the other of the pair of antennas to receive a partial discharge signal of a frequency different from a partial discharge signal to be received by the other of the pair of antennas.

29. The method as claimed in claim 28, wherein coupling the vertical-cavity surface-emitting laser to the antenna comprises integrating the vertical-cavity surface-emitting laser in the antenna.

5 30. The method as claimed in claim 28, wherein coupling the vertical-cavity surface-emitting laser to the antenna comprises coupling via an electrical interconnection.

31. The method as claimed in claim 30, wherein the electrical interconnection is an RF cable.

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32. The method as claimed in claim 31, further comprising coupling the RF cable to the vertical-cavity surface-emitting laser via an SMA connector or a BNC connector connected to an anode and a cathode of the vertical-cavity surface-emitting laser.

15 33. The method as claimed in any one of claims 28 to 32, further comprising coupling a biasing circuit to the vertical-cavity surface-emitting laser.

34. The method as claimed in any one of claims 28 to 33, further comprising coupling an amplifying circuit to the vertical-cavity surface-emitting laser.

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35. The method as claimed in any one of claims 28 to 34, further comprising coupling an optical waveguide to the vertical-cavity surface-emitting laser, the optical waveguide configured to transmit the optical signal.

25 36. The method as claimed in claim 35, wherein the optical waveguide is an optical fiber.

37. The method as claimed in any one of claims 28 to 36, wherein the optical signal has a different frequency from that of the partial discharge signal.

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38. The method as claimed in any one of claims 28 to 37, wherein the antenna is operable in a frequency range of between about 100 kHz to about 1 GHz.

39. The method as claimed in any one of claims 28 to 38, further comprising coupling
5 a second antenna to the vertical-cavity surface-emitting laser.

40. A method of forming a system for detecting a partial discharge signal, the method comprising:

manufacturing at least one sensor using the method as claimed in any one of
10 claims 28 to 39; and

coupling at least one detector to the at least one sensor, wherein the at least one detector is configured to detect the optical signal from the at least one sensor and convert the optical signal into an electrical signal.

41. The method as claimed in claim 40, further comprising providing a data acquisition circuit configured to convert the electrical signal from the at least one sensor into a digital signal.
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42. The method as claimed in claim 40, further comprising providing a processing
20 device configured to process the digital signal.

43. The method as claimed in any one of claims 40 to 42, wherein manufacturing the at least one sensor comprises forming a plurality of sensors, and wherein each of the plurality of sensors is configured to receive a respective partial discharge signal and
25 convert the respective received partial discharge signal into a respective optical signal.

44. The method as claimed in claim 43, wherein coupling the at least one detector comprises coupling a plurality of detectors, and wherein each of the plurality of detectors is configured to detect the respective optical signal and convert the respective optical
30 signal into a respective electrical signal.

45. The method as claimed in claim 44, further comprising providing an optical cable comprising a plurality of optical fibers, and coupling a respective optical fiber of the plurality of optical fibers to a respective detector of the plurality of detectors and a respective sensor of the plurality of sensors.

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46. The method as claimed in any one of claims 43 to 45, further comprising coupling an optical switch to the plurality of sensors.

47. The method as claimed in any one of claims 43 to 46, wherein a respective
10 wavelength of the respective optical signal is different.

48. The method as claimed in claim 47, further comprising:
providing at least one coupler configured to combine the respective optical signal;
and

15 providing a demultiplexer configured to receive and demultiplex the combined optical signal.

49. The method as claimed in claim 48, wherein the at least one coupler is a 1×2 coupler configured to combine two respective optical signals into the combined signal.

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50. The method as claimed in claim 49, wherein the 1×2 coupler has a coupling ratio selected from a group consisting of 10/90, 20/80, 30/70, 40/60 and 50/50.

51. The method as claimed in claim 49 or 50, wherein providing the at least one
25 coupler comprises providing a plurality of couplers, wherein the number of the plurality of couplers is one less than the number of the plurality of sensors.

52. The method as claimed in any one of claims 48 to 51, further comprising coupling the at least one coupler to the demultiplexer via an optical fiber.

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53. The method as claimed in claim 47, further comprising:

providing a multiplexer configured to multiplex the respective optical signal; and
providing a demultiplexer configured to receive and demultiplex the multiplexed
optical signal.

5 54. The method as claimed in claim 53, further comprising coupling the multiplexer
to the demultiplexer via an optical fiber.

55. A method of detecting a partial discharge signal, the method comprising:
receiving a partial discharge signal by an antenna; and
10 converting the received partial discharge signal into an optical signal by a
vertical-cavity surface-emitting laser coupled to the antenna.

wherein the antenna comprises a pair of antennas coupled in series to each other,
each of the pair of antennas comprising a pair of elements arranged as mirror images of
each other about a central axis of the pair of elements, each element of the pair of
15 elements comprising a continuous rectangular serpentine line,

wherein each of the pair of antennas is dimensioned differently from the other of
the pair of antennas, and

wherein receiving a partial discharge signal comprises receiving, by one of the
pair of antennas, a partial discharge signal of a frequency different from a partial
20 discharge signal to be received by the other of the pair of antennas.

56. The method as claimed in claim 55, further comprising converting the optical
signal into an electrical signal.

25 57. The method as claimed in claim 56, further comprising converting the electrical
signal into a digital signal.

58. The method as claimed in claim 57, further comprising processing the digital
signal.

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