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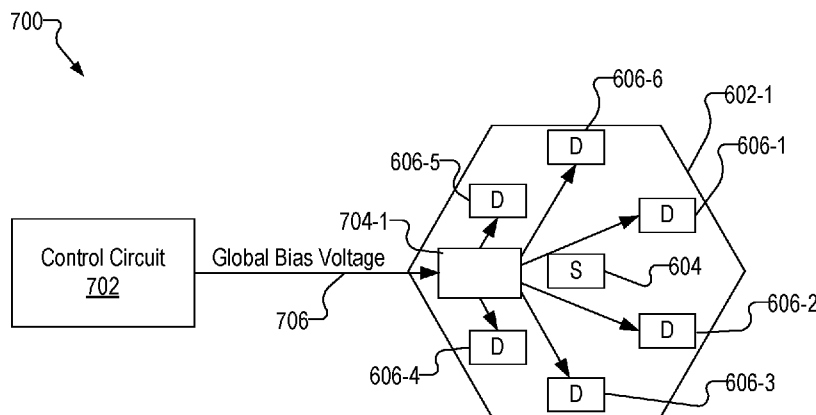


Fig. 7

(57) Abstract: An exemplary optical measurement system described herein includes a control circuit configured to output a global bias voltage and a module communicatively coupled to the control circuit. The module includes a light source configured to emit light directed at a target. The module further includes a plurality of detectors configured to detect arrival times for photons of the light after the light is scattered by the target. The module further includes a module control circuit configured to receive the global bias voltage and output a plurality of detector bias voltages based on the global bias voltage. The plurality of detector bias voltages include a respective detector bias voltage for each detector of the plurality of detectors.



BIAS VOLTAGE GENERATION IN AN OPTICAL MEASUREMENT SYSTEM

RELATED APPLICATIONS

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[0001] The present application claims priority to U.S. Provisional Patent Application No. 62/992,510, filed on March 20, 2020, and to U.S. Provisional Patent Application No. 63/057,080, filed on July 27, 2020. These applications are incorporated herein by reference in their respective entireties.

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BACKGROUND INFORMATION

[0002] Detecting neural activity in the brain (or any other turbid medium) is useful for medical diagnostics, imaging, neuroengineering, brain-computer interfacing, and a variety of other diagnostic and consumer-related applications. For example, it may be desirable to detect neural activity in the brain of a user to determine if a particular region of the brain has been impacted by reduced blood irrigation, a hemorrhage, or any other type of damage. As another example, it may be desirable to detect neural activity in the brain of a user and computationally decode the detected neural activity into commands that can be used to control various types of consumer electronics (e.g., by controlling a cursor on a computer screen, changing channels on a television, turning lights on, etc.).

[0003] Neural activity and other attributes of the brain may be determined or inferred by measuring responses of tissue within the brain to light pulses. One technique to measure such responses is time-correlated single-photon counting (TCSPC). Time-correlated single-photon counting detects single photons and measures a time of arrival of the photons with respect to a reference signal (e.g., a light source). By repeating the light pulses, TCSPC may accumulate a sufficient number of photon events to statistically determine a histogram representing the distribution of detected photons. Based on the histogram of photon distribution, the response of tissue to light pulses may be determined in order to study the detected neural activity and/or other attributes of the brain.

[0004] A photodetector capable of detecting a single photon (i.e., a single particle of optical energy) is an example of a non-invasive detector that can be used in an optical measurement system to detect neural activity within the brain. An exemplary photodetector is implemented by a semiconductor-based single-photon avalanche

diode (SPAD), which is capable of capturing individual photons with very high time-of-arrival resolution (a few tens of picoseconds).

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BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The accompanying drawings illustrate various embodiments and are a part of the specification. The illustrated embodiments are merely examples and do not limit the scope of the disclosure. Throughout the drawings, identical or similar reference
10 numbers designate identical or similar elements.

[0006] FIG. 1 shows an exemplary optical measurement system.

[0007] FIG. 2 illustrates an exemplary detector architecture.

[0008] FIG. 3 illustrates an exemplary timing diagram for performing an optical measurement operation using an optical measurement system.

15 **[0009]** FIG. 4 illustrates a graph of an exemplary temporal point spread function that may be generated by an optical measurement system in response to a light pulse.

[0010] FIG. 5 shows an exemplary non-invasive wearable brain interface system.

[0011] FIG. 6 shows an exemplary wearable module assembly.

[0012] FIGS. 7-8 show exemplary configurations of a wearable module assembly.

20 **[0013]** FIG. 9 shows an exemplary circuit of a wearable module assembly.

[0014] FIG. 10 shows another exemplary configuration of a wearable module assembly.

[0015] FIGS. 11-16 illustrate embodiments of a wearable device that includes elements of the optical measurement systems described herein.

25 **[0016]** FIG. 17 illustrates an exemplary computing device.

[0017] FIG. 18 illustrates an exemplary method.

DETAILED DESCRIPTION

30 **[0018]** Systems, circuits, and methods for bias voltage generation in an optical measurement system are described herein. For example, a control circuit may output a global bias voltage for a plurality of modules of the optical measurement system. Each module may include a module control circuit that receives the global bias voltage and adjusts a voltage level of the global bias voltage to output a plurality of detector bias

voltages. The plurality of detector bias voltages may include a different detector bias voltage for each detector included within the module. In this manner, the optical measurement system may provide detector bias voltages at different (or same) voltage levels for each detector based on an optimal bias voltage of the detector.

5 **[0019]** Systems, circuits, and methods described herein may allow the optical measurement system to efficiently and concurrently provide a plurality of detector bias voltages to different detectors of different modules in an optical measurement system. For instance, outputting a global bias voltage that is adjusted at each module may allow for reduced complexity in coupling the control circuit to the modules. Further, voltage
10 levels of the global bias voltage may be selected and/or adjusted to efficiently use resources, such as by reducing power dissipation.

[0020] These and other advantages and benefits of the present systems, circuits, and methods are described more fully herein.

[0021] FIG. 1 shows an exemplary optical measurement system 100 configured to
15 perform an optical measurement operation with respect to a body 102. Optical measurement system 100 may, in some examples, be portable and/or wearable by a user. Optical measurement systems that may be used in connection with the embodiments described herein are described more fully in U.S. Patent Application No. 17/176,315, filed February 16, 2021; U.S. Patent Application No. 17/176,309, filed
20 February 16, 2021; U.S. Patent Application No. 17/176,460, filed February 16, 2021; U.S. Patent Application No. 17/176,470, filed February 16, 2021; U.S. Patent Application No. 17/176,487, filed February 16, 2021; U.S. Patent Application No. 17/176,539, filed February 16, 2021; U.S. Patent Application No. 17/176,560, filed February 16, 2021; and U.S. Patent Application No. 17/176,466, filed February 16,
25 2021, which applications are incorporated herein by reference in their entirety.

[0022] In some examples, optical measurement operations performed by optical measurement system 100 are associated with a time domain-based optical measurement technique. Example time domain-based optical measurement techniques include, but are not limited to, time-correlated single-photon counting (TCSPC), time
30 domain near infrared spectroscopy (TD-NIRS), time domain diffusive correlation spectroscopy (TD-DCS), and time domain Digital Optical Tomography (TD-DOT). For example, TCSPC detects single photons and measures a time of arrival of the photons with respect to a reference signal (e.g., a light source). By repeating the light pulses, TCSPC may accumulate a sufficient number of photon events to statistically determine

a histogram representing the distribution of detected photons. Based on the histogram of photon distribution, the response of tissue to light pulses may be determined in order to study the detected neural activity and/or other attributes of the brain.

[0023] As shown, optical measurement system 100 includes a detector 104 that includes a plurality of individual photodetectors (e.g., photodetector 106), a processor 108 coupled to detector 104, a light source 110, a controller 112, and optical conduits 114 and 116 (e.g., light pipes). However, one or more of these components may not, in certain embodiments, be considered to be a part of optical measurement system 100. For example, in implementations where optical measurement system 100 is wearable by a user, processor 108 and/or controller 112 may in some embodiments be separate from optical measurement system 100 and not configured to be worn by the user.

[0024] Detector 104 may include any number of photodetectors 106 as may serve a particular implementation, such as 2^n photodetectors (e.g., 256, 512, ..., 16384, etc.), where n is an integer greater than or equal to one (e.g., 4, 5, 8, 10, 11, 14, etc.). Photodetectors 106 may be arranged in any suitable manner.

[0025] Photodetectors 106 may each be implemented by any suitable circuit configured to detect individual photons of light incident upon photodetectors 106. For example, each photodetector 106 may be implemented by a single photon avalanche diode (SPAD) circuit and/or other circuitry as may serve a particular implementation.

[0026] Processor 108 may be implemented by one or more physical processing (e.g., computing) devices. In some examples, processor 108 may execute instructions (e.g., software) configured to perform one or more of the operations described herein.

[0027] Light source 110 may be implemented by any suitable component configured to generate and emit light. For example, light source 110 may be implemented by one or more laser diodes, distributed feedback (DFB) lasers, super luminescent diodes (SLDs), light emitting diodes (LEDs), diode-pumped solid-state (DPSS) lasers, super luminescent light emitting diodes (sLEDs), vertical-cavity surface-emitting lasers (VCSELs), titanium sapphire lasers, micro light emitting diode (mLEDs), and/or any other suitable laser or light source. In some examples, the light emitted by light source 110 is high coherence light (e.g., light that has a coherence length of at least 5 centimeters) at a predetermined center wavelength.

[0028] Light source 110 is controlled by controller 112, which may be implemented by any suitable computing device (e.g., processor 108), integrated circuit, and/or combination of hardware and/or software as may serve a particular implementation. In

some examples, controller 112 is configured to control light source 110 by turning light source 110 on and off and/or setting an intensity of light generated by light source 110. Controller 112 may be manually operated by a user, or may be programmed to control light source 110 automatically.

5 **[0029]** Light emitted by light source 110 may travel via an optical conduit 114 (e.g., a light pipe, a light guide, a waveguide, a single-mode optical fiber, and/or or a multi-mode optical fiber) to body 102 of a subject. In cases where optical conduit 114 is implemented by a light guide, the light guide may be spring loaded and/or have a cantilever mechanism to allow for conformably pressing the light guide firmly against
10 body 102.

[0030] Body 102 may include any suitable turbid medium. For example, in some implementations, body 102 is a head or any other body part of a human or other animal. Alternatively, body 102 may be a non-living object. For illustrative purposes, it will be assumed in the examples provided herein that body 102 is a human head.

15 **[0031]** As indicated by arrow 120, the light emitted by light source 110 enters body 102 at a first location 122 on body 102. Accordingly, a distal end of optical conduit 114 may be positioned at (e.g., right above or physically attached to) first location 122 (e.g., to a scalp of the subject). In some examples, the light may emerge from optical conduit 114 and spread out to a certain spot size on body 102 to fall under a predetermined
20 safety limit.

[0032] As used herein, "distal" means nearer, along the optical path of the light emitted by light source 110 or the light received by detector 104, to the target (e.g., within body 102) than to light source 110 or detector 104. Thus, the distal end of optical conduit 114 is nearer to body 102 than to light source 110, and the distal end of optical
25 conduit 116 is nearer to body 102 than to detector 104. Additionally, as used herein, "proximal" means nearer, along the optical path of the light emitted by light source 110 or the light received by detector 104, to light source 110 or detector 104 than to body 102. Thus, the proximal end of optical conduit 114 is nearer to light source 110 than to body 102, and the proximal end of optical conduit 116 is nearer to detector 104 than to
30 body 102.

[0033] As shown, the distal end of optical conduit 116 (e.g., a light pipe, a single-mode optical fiber, and/or or a multi-mode optical fiber) is positioned at (e.g., right above or physically attached to) output location 126 on body 102. In this manner, optical conduit 116 may collect light 124 as it exits body 102 at location 126 and carry

the light to detector 104. The light may pass through one or more lenses and/or other optical elements (not shown) that direct the light onto each of the photodetectors 106 included in detector 104.

[0034] Photodetectors 106 may be connected in parallel in detector 104. An output of each of photodetectors 106 may be accumulated to generate an accumulated output of detector 104. Processor 108 may receive the accumulated output and determine, based on the accumulated output, a temporal distribution of photons detected by photodetectors 106. Processor 108 may then generate, based on the temporal distribution, a histogram representing a light pulse response of a target (e.g., brain tissue, blood flow, etc.) in body 102. Example embodiments of accumulated outputs are described herein.

[0035] FIG. 2 illustrates an exemplary detector architecture 200 that may be used in accordance with the systems and methods described herein. As shown, architecture 200 includes a SPAD circuit 202 that implements photodetector 106, a control circuit 204, a time-to-digital converter (TDC) 206, and a signal processing circuit 208. Architecture 200 may include additional or alternative components as may serve a particular implementation.

[0036] In some examples, SPAD circuit 202 includes a SPAD and a fast gating circuit configured to operate together to detect a photon incident upon the SPAD. As described herein, SPAD circuit 202 may generate an output when SPAD circuit 202 detects a photon.

[0037] The fast gating circuit included in SPAD circuit 202 may be implemented in any suitable manner. For example, the fast gating circuit may include a capacitor that is pre-charged with a bias voltage before a command is provided to arm the SPAD. Gating the SPAD with a capacitor instead of with an active voltage source, such as is done in some conventional SPAD architectures, has a number of advantages and benefits. For example, a SPAD that is gated with a capacitor may be armed practically instantaneously compared to a SPAD that is gated with an active voltage source. This is because the capacitor is already charged with the bias voltage when a command is provided to arm the SPAD. This is described more fully in U.S. Patent Nos. 10,158,038 and 10,424,683, which are incorporated herein by reference in their entireties.

[0038] In some alternative configurations, SPAD circuit 202 does not include a fast gating circuit. In these configurations, the SPAD included in SPAD circuit 202 may be

gated in any suitable manner or be configured to operate in a free running mode with passive quenching.

[0039] Control circuit 204 may be implemented by an application specific integrated circuit (ASIC) or any other suitable circuit configured to control an operation of various components within SPAD circuit 202. For example, control circuit 204 may output control logic that puts the SPAD included in SPAD circuit 202 in either an armed or a disarmed state.

[0040] In some examples, control circuit 204 may control a gate delay, which specifies a predetermined amount of time control circuit 204 is to wait after an occurrence of a light pulse (e.g., a laser pulse) to put the SPAD in the armed state. To this end, control circuit 204 may receive light pulse timing information, which indicates a time at which a light pulse occurs (e.g., a time at which the light pulse is applied to body 102). Control circuit 204 may also control a programmable gate width, which specifies how long the SPAD is kept in the armed state before being disarmed.

[0041] Control circuit 204 is further configured to control signal processing circuit 208. For example, control circuit 204 may provide histogram parameters (e.g., time bins, number of light pulses, type of histogram, etc.) to signal processing circuit 208. Signal processing circuit 208 may generate histogram data in accordance with the histogram parameters. In some examples, control circuit 204 is at least partially implemented by controller 112.

[0042] TDC 206 is configured to measure a time difference between an occurrence of an output pulse generated by SPAD circuit 202 and an occurrence of a light pulse. To this end, TDC 206 may also receive the same light pulse timing information that control circuit 204 receives. TDC 206 may be implemented by any suitable circuitry as may serve a particular implementation.

[0043] Signal processing circuit 208 is configured to perform one or more signal processing operations on data output by TDC 206. For example, signal processing circuit 208 may generate histogram data based on the data output by TDC 206 and in accordance with histogram parameters provided by control circuit 204. To illustrate, signal processing circuit 208 may generate, store, transmit, compress, analyze, decode, and/or otherwise process histograms based on the data output by TDC 206. In some examples, signal processing circuit 208 may provide processed data to control circuit 204, which may use the processed data in any suitable manner. In some

examples, signal processing circuit 208 is at least partially implemented by processor 108.

[0044] In some examples, each photodetector 106 (e.g., SPAD circuit 202) may have a dedicated TDC 206 associated therewith. For example, for an array of N photodetectors 106, there may be a corresponding array of N TDCs 206. Alternatively, a single TDC 206 may be associated with multiple photodetectors 106. Likewise, a single control circuit 204 and a single signal processing circuit 208 may be provided for a one or more photodetectors 106 and/or TDCs 206.

[0045] FIG. 3 illustrates an exemplary timing diagram 300 for performing an optical measurement operation using optical measurement system 100. Optical measurement system 100 may be configured to perform the optical measurement operation by directing light pulses (e.g., laser pulses) toward a target within a body (e.g., body 102). The light pulses may be short (e.g., 10-2000 picoseconds (ps)) and repeated at a high frequency (e.g., between 100,000 hertz (Hz) and 100 megahertz (MHz)). The light pulses may be scattered by the target and then detected by optical measurement system 100. Optical measurement system 100 may measure a time relative to the light pulse for each detected photon. By counting the number of photons detected at each time relative to each light pulse repeated over a plurality of light pulses, optical measurement system 100 may generate a histogram that represents a light pulse response of the target (e.g., a temporal point spread function (TPSF)). The terms histogram and TPSF are used interchangeably herein to refer to a light pulse response of a target.

[0046] For example, timing diagram 300 shows a sequence of light pulses 302 (e.g., light pulses 302-1 and 302-2) that may be applied to the target (e.g., tissue within a brain of a user, blood flow, a fluorescent material used as a probe in a body of a user, etc.). Timing diagram 300 also shows a pulse wave 304 representing predetermined gated time windows (also referred as gated time periods) during which photodetectors 106 are gated ON to detect photons. Referring to light pulse 302-1, light pulse 302-1 is applied at a time t_0 . At a time t_1 , a first instance of the predetermined gated time window begins. Photodetectors 106 may be armed at time t_1 , enabling photodetectors 106 to detect photons scattered by the target during the predetermined gated time window. In this example, time t_1 is set to be at a certain time after time t_0 , which may minimize photons detected directly from the laser pulse, before the laser pulse reaches the target. However, in some alternative examples, time t_1 is set to be equal to time t_0 .

[0047] At a time t_2 , the predetermined gated time window ends. In some examples, photodetectors 106 may be disarmed at time t_2 . In other examples, photodetectors 106 may be reset (e.g., disarmed and re-armed) at time t_2 or at a time subsequent to time t_2 . During the predetermined gated time window, photodetectors 106 may detect photons scattered by the target. Photodetectors 106 may be configured to remain armed during the predetermined gated time window such that photodetectors 106 maintain an output upon detecting a photon during the predetermined gated time window. For example, a photodetector 106 may detect a photon at a time t_3 , which is during the predetermined gated time window between times t_1 and t_2 . The photodetector 106 may be configured to provide an output indicating that the photodetector 106 has detected a photon. The photodetector 106 may be configured to continue providing the output until time t_2 , when the photodetector may be disarmed and/or reset. Optical measurement system 100 may generate an accumulated output from the plurality of photodetectors. Optical measurement system 100 may sample the accumulated output to determine times at which photons are detected by photodetectors 106 to generate a TPSF.

[0048] As mentioned, in some alternative examples, photodetector 106 may be configured to operate in a free-running mode such that photodetector 106 is not actively armed and disarmed (e.g., at the end of each predetermined gated time window represented by pulse wave 304). In contrast, while operating in the free-running mode, photodetector 106 may be configured to reset within a configurable time period after an occurrence of a photon detection event (i.e., after photodetector 106 detects a photon) and immediately begin detecting new photons. However, only photons detected within a desired time window (e.g., during each gated time window represented by pulse wave 304) may be included in the TPSF.

[0049] FIG. 4 illustrates a graph 400 of an exemplary TPSF 402 that may be generated by optical measurement system 100 in response to a light pulse 404 (which, in practice, represents a plurality of light pulses). Graph 400 shows a normalized count of photons on a y-axis and time bins on an x-axis. As shown, TPSF 402 is delayed with respect to a temporal occurrence of light pulse 404. In some examples, the number of photons detected in each time bin subsequent to each occurrence of light pulse 404 may be aggregated (e.g., integrated) to generate TPSF 402. TPSF 402 may be analyzed and/or processed in any suitable manner to determine or infer detected neural activity.

[0050] Optical measurement system 100 may be implemented by or included in any suitable device. For example, optical measurement system 100 may be included, in whole or in part, in a non-invasive wearable device (e.g., a headpiece) that a user may wear to perform one or more diagnostic, imaging, analytical, and/or consumer-related operations. The non-invasive wearable device may be placed on a user's head or other part of the user to detect neural activity. In some examples, such neural activity may be used to make behavioral and mental state analysis, awareness and predictions for the user.

[0051] Mental state described herein refers to the measured neural activity related to physiological brain states and/or mental brain states, e.g., joy, excitement, relaxation, surprise, fear, stress, anxiety, sadness, anger, disgust, contempt, contentment, calmness, focus, attention, approval, creativity, positive or negative reflections/attitude on experiences or the use of objects, etc. Further details on the methods and systems related to a predicted brain state, behavior, preferences, or attitude of the user, and the creation, training, and use of neuromes can be found in U.S. Provisional Patent Application No. 63/047,991, filed July 3, 2020. Exemplary measurement systems and methods using biofeedback for awareness and modulation of mental state are described in more detail in U.S. Patent Application No. 16/364,338, filed March 26, 2019, published as US2020/0196932A1. Exemplary measurement systems and methods used for detecting and modulating the mental state of a user using entertainment selections, e.g., music, film/video, are described in more detail in U.S. Patent Application No. 16/835,972, filed March 31, 2020, published as US2020/0315510A1. Exemplary measurement systems and methods used for detecting and modulating the mental state of a user using product formulation from, e.g., beverages, food, selective food/drink ingredients, fragrances, and assessment based on product-elicited brain state measurements are described in more detail in U.S. Patent Application No. 16/853,614, filed April 20, 2020, published as US2020/0337624A1. Exemplary measurement systems and methods used for detecting and modulating the mental state of a user through awareness of priming effects are described in more detail in U.S. Patent Application No. 16/885,596, filed May 28, 2020, published as US2020/0390358A1. These applications and corresponding U.S. publications are incorporated herein by reference in their entirety.

[0052] FIG. 5 shows an exemplary non-invasive wearable brain interface system 500 ("brain interface system 500") that implements optical measurement system 100

(shown in FIG. 1). As shown, brain interface system 500 includes a head-mountable component 502 configured to be attached to a user's head. Head-mountable component 502 may be implemented by a cap shape that is worn on a head of a user. Alternative implementations of head-mountable component 502 include helmets, beanies, headbands, other hat shapes, or other forms conformable to be worn on a user's head, etc. Head-mountable component 502 may be made out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation. Examples of headgears used with wearable brain interface systems are described more fully in U.S. Patent No. 10,340,408, incorporated herein by reference in its entirety.

[0053] Head-mountable component 502 includes a plurality of detectors 504, which may implement or be similar to detector 104, and a plurality of light sources 506, which may be implemented by or be similar to light source 110. It will be recognized that in some alternative embodiments, head-mountable component 502 may include a single detector 504 and/or a single light source 506.

[0054] Brain interface system 500 may be used for controlling an optical path to the brain and for transforming photodetector measurements into an intensity value that represents an optical property of a target within the brain. Brain interface system 500 allows optical detection of deep anatomical locations beyond skin and bone (e.g., skull) by extracting data from photons originating from light source 506 and emitted to a target location within the user's brain, in contrast to conventional imaging systems and methods (e.g., optical coherence tomography (OCT)), which only image superficial tissue structures or through optically transparent structures.

[0055] Brain interface system 500 may further include a processor 508 configured to communicate with (e.g., control and/or receive signals from) detectors 504 and light sources 506 by way of a communication link 510. Communication link 510 may include any suitable wired and/or wireless communication link. Processor 508 may include any suitable housing and may be located on the user's scalp, neck, shoulders, chest, or arm, as may be desirable. In some variations, processor 508 may be integrated in the same assembly housing as detectors 504 and light sources 506.

[0056] As shown, brain interface system 500 may optionally include a remote processor 512 in communication with processor 508. For example, remote processor 512 may store measured data from detectors 504 and/or processor 508 from previous detection sessions and/or from multiple brain interface systems (not shown). Power for

detectors 504, light sources 506, and/or processor 508 may be provided via a wearable battery (not shown). In some examples, processor 508 and the battery may be enclosed in a single housing, and wires carrying power signals from processor 508 and the battery may extend to detectors 504 and light sources 506. Alternatively, power
5 may be provided wirelessly (e.g., by induction).

[0057] In some alternative embodiments, head mountable component 502 does not include individual light sources. Instead, a light source configured to generate the light that is detected by detector 504 may be included elsewhere in brain interface system 500. For example, a light source may be included in processor 508 and coupled to
10 head mountable component 502 through optical connections.

[0058] Optical measurement system 100 may alternatively be included in a non-wearable device (e.g., a medical device and/or consumer device that is placed near the head or other body part of a user to perform one or more diagnostic, imaging, and/or consumer-related operations). Optical measurement system 100 may alternatively be
15 included in a sub-assembly enclosure of a wearable invasive device (e.g., an implantable medical device for brain recording and imaging).

[0059] Optical measurement system 100 may be modular in that one or more components of optical measurement system 100 may be removed, changed out, or otherwise modified as may serve a particular implementation. Additionally or
20 alternatively, optical measurement system 100 may be modular such that one or more components of optical measurement system 100 may be housed in a separate housing (e.g., module) and/or may be movable relative to other components. Exemplary modular multimodal measurement systems are described in more detail in U.S. Provisional Patent Application No. 17/176,460, filed February 16, 2021, U.S. Provisional Patent Application No. 17/176,470, filed February 16, 2021, U.S. Provisional Patent Application No. 17/176,487, filed February 16, 2021, U.S. Provisional Patent Application No. 63/038,481, filed February 16, 2021, and U.S. Provisional Patent Application No. 17/176,560, filed February 16, 2021, which applications are incorporated herein by reference in their respective entireties.

[0060] To illustrate, FIG. 6 shows an exemplary wearable module assembly 600 ("assembly 600") that implements one or more of the optical measurement features described herein. Assembly 600 may be worn on the head or any other suitable body part of the user. As shown, assembly 600 may include a plurality of modules 602 (e.g., modules 602-1 through 602-3). While three modules 602 are shown to be included in
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assembly 600 in FIG. 6, in alternative configurations, any number of modules 602 (e.g., a single module up to sixteen or more modules) may be included in assembly 600. Moreover, while modules 602 are shown to be adjacent to and touching one another, modules 602 may alternatively be spaced apart from one another (e.g., in
5 implementations where modules 602 are configured to be inserted into individual slots or cutouts of the headgear). Moreover, while modules 602 are shown to have a hexagonal shape, modules 602 may alternatively have any other suitable geometry (e.g., in the shape of a pentagon, octagon, square, rectangular, circular, triangular, free-
10 form, etc.). Assembly 600 may conform to three-dimensional surface geometries, such as a user's head. Exemplary wearable module assemblies comprising a plurality of wearable modules are described in more detail in U.S. Provisional Patent Application No. 62/992,550, filed March 20, 2020, U.S. Provisional Patent Application No. 63/038,459, filed June 12, 2020, and U.S. Provisional Patent Application No. 63/038,468, filed June 12, 2020, which applications are incorporated herein by
15 reference in their respective entireties.

[0061] Each module 602 includes a source 604 and a plurality of detectors 606 (e.g., detectors 606-1 through 606-6). Source 604 may be implemented by one or more light sources similar to light source 110. Each detector 606 may implement or be similar to detector 104 and may include a plurality of photodetectors (e.g., SPADs) as well as
20 other circuitry (e.g., TDCs). As shown, detectors 606 are arranged around and substantially equidistant from source 604. In other words, the spacing between a light source (i.e., a distal end portion of a light source optical conduit) and the detectors (i.e., distal end portions of optical conduits for each detector) are maintained at the same fixed distance on each module to ensure homogeneous coverage over specific areas
25 and to facilitate processing of the detected signals. The fixed spacing also provides consistent spatial (lateral and depth) resolution across the target area of interest, e.g., brain tissue. Moreover, maintaining a known distance between the light emitter and the detector allows subsequent processing of the detected signals to infer spatial (e.g., depth localization, inverse modeling) information about the detected signals. Detectors
30 606 may be alternatively disposed as may serve a particular implementation.

[0062] As described, each module 602 includes detectors 606. Each detector 606 may have an optimal bias voltage level for operating the plurality of photodetectors of detector 606. While the optimal bias voltage levels for detectors 606 may be designed to be a same bias voltage level for all detectors 606, actual optimal bias voltage levels

may differ from detector to detector. For instance, manufacturing process variations, temperature variations, and other types of variations may result in different optimal bias voltages for detectors 606. Further, optimal bias voltage levels may vary over time (e.g., as temperatures or other characteristics change that may affect the optimal bias

5 voltages). Thus, optical measurement system 100 may be configured to provide different detector bias voltages for each detector 606 of each module 602.

[0063] FIG. 7 shows an exemplary configuration 700 of components of an optical measurement system (e.g., optical measurement system 100). Configuration 700 shows module 602-1 (shown in FIG. 6) communicatively coupled to a control circuit 702

10 (e.g., an implementation or component of processor 508). Configuration 700 also shows module 602-1 including a module control circuit 704-1 communicatively coupled to control circuit 702 via a communication bus 706.

[0064] Control circuit 702 may be configured to output a global bias voltage. Control circuit 702 may generate the global bias voltage in any suitable manner, using any

15 suitable circuits and/or components that generate a voltage. The global bias voltage may be provided to module control circuit 704-1. Module control circuit 704-1 may receive the global bias voltage and adjust a voltage level of the global bias voltage to output a plurality of detector bias voltages including a detector bias voltage for each detector 606 of module 602-1.

[0065] For instance, control circuit 702 may be configured to output the global bias voltage at a voltage level that is higher than an optimal bias voltage level for each of detectors 606. For example, if the optimal bias voltage level for detectors 606 range from 14 volts (V) to 15 V, control circuit 702 may output a global bias voltage of 18 V (or any other value greater than the optimal bias voltages for detectors 606).

[0066] Module control circuit 704-1 may receive the global bias voltage and step down the global bias voltage to output a detector bias voltage for each of detectors 606 based on the optimal bias voltage level for each detector 606. This detector bias voltage is represented in FIG. 7 by the arrows that interconnect module control circuit 704-1 and each of detectors 606. In the configuration shown in FIG. 7, there are six

25 arrows representing the interconnection between the module control circuit 704-1 and each detector (e.g., detectors 606-1 through 606-6).

[0067] For example, if detector 606-1 has an optimal bias voltage level of 14.5 V, module control circuit 704-1 may step down the global bias voltage of 18 V to 14.5 V and output 14.5 V as the detector bias voltage for detector 606-1. Module control circuit

704-1 may similarly step down the global bias voltage for each of detectors 606-2 through 606-6 to provide detector bias voltages that correspond to optimal bias voltage levels for each respective detector. Module control circuit 704-1 may step down the voltage using any suitable circuits and/or components that step down a voltage level, such as a low-dropout (LDO) regulator (as described further herein) or any other such circuit.

[0068] Module control circuit 704-1 may be further configured to measure the optimal bias voltage level for each of detectors 606. Module control circuit 704-1 may measure the optimal bias voltage level for each detector 606 in any suitable manner.

[0069] Module control circuit 704-1 may additionally or alternatively receive and/or otherwise access data representative of the optimal bias voltage level for each detector 606. For example, each detector 606 may be configured to measure the optimal bias voltage level and provide a signal representative of the measured optimal bias voltage level to module circuit 704-1.

[0070] Module control circuit 704-1 may use the measured optimal bias voltage level for each detector 606 to determine the voltage level for each detector bias voltage. For instance, module control circuit 704-1 may step down the global bias voltage to match the measured optimal bias voltage level for each detector bias voltage for each respective detector 606. Consequently, if the optimal bias voltage level for a particular detector 606 changes, module control circuit 704-1 may adjust the voltage level of the detector bias voltage to continue to output a detector bias voltage that is optimal for the particular detector 606.

[0071] In some examples, module control circuit 704-1 may provide a signal (e.g., data) representative of the measured optimal bias voltage level to control circuit 702 so that control circuit 702 may output a global bias voltage level based on the measured optimal bias voltage levels. For example, control circuit 702 may receive a signal representative of the measured optimal bias voltage level of detectors 606-1 through 606-6 and output a global bias voltage level that is a predetermined amount higher than a highest voltage level of the measured optimal bias voltage levels. Alternatively, module control circuit 704-1 may transmit a signal representative of the highest voltage level of the measured optimal bias voltage levels to control circuit 702 so that control circuit 702 may output the global bias voltage level accordingly. In this manner, control circuit 702 may monitor the plurality of detector bias voltages and adjust the global bias

voltage so that power dissipation from stepping down the global bias voltage to the detector bias voltages may be minimized.

[0072] In other examples, optimal bias voltage levels of detectors 606 may be determined based on measurements performed during a testing period, such as during manufacturing, calibration, and/or any other quality control testing periods. Control circuit 702 may be configured to output the global bias voltage based on a highest voltage level measured and/or estimated during the testing period. Additionally or alternatively, control circuit 702 may be configured to output the global bias voltage based on a highest voltage level as designed and/or modeled for detectors 606 and/or in accordance with any other suitable factors.

[0073] In some examples, control circuit 702 may be configured to output the global bias voltage at a voltage level that is lower than the optimal bias voltage level for each of detectors 606. In these examples, module control circuit 704-1 may receive the global bias voltage and step up the global bias voltage to output a detector bias voltage for each of detectors 606 based on the optimal bias voltage level for each detector 606. Module control circuit 704-1 may step up the voltage using any suitable circuits and/or components that step up a voltage level, such as a charge pump or any other such circuit.

[0074] In some examples, control circuit 702 may be configured to output the global bias voltage at a voltage level that may be lower than some of the optimal bias voltage levels for detectors 606 and higher than others. For instance, control circuit 702 may base the voltage level of the global bias voltage on some characteristic and/or factor of optical measurement system 100 other than the optimal bias voltage levels of detectors 606. In such a case, module control circuit 704-1 may step up or step down the global bias voltage level as appropriate for each detector bias voltage for each respective detector 606.

[0075] FIG. 8 shows an exemplary configuration 800 of components of an optical measurement system (e.g., optical measurement system 100). Configuration 800 may include control circuit 702 and module 602-1 as described in configuration 700 of FIG. 7. Configuration 800 also shows modules 602-2 and 602-3 configured in a manner similar to module 602-1. For example, module 602-2 includes module control circuit 704-2 and module 602-3 includes module control circuit 704-3. Module control circuits 704-2 and 704-3 are also connected to control circuit 702. Module control circuits 704 may be connected to control circuit 702 via communication bus 706.

[0076] As described with respect to module 602-1, modules 602-2 and 602-3 may also receive a global bias voltage output by control circuit 702. Module control circuits 704-2 and 704-3 may also similarly output a plurality of detector bias voltages for the detectors of modules 602-2 and 602-3, respectively. Thus, optical measurement system 100 may be configured to provide different detector bias voltages for each detector in optical measurement system 100. The different detector bias voltages may each be generated by adjusting from a single global bias voltage output by control circuit 702. Consequently, communication bus 706 may be implemented as a single bus (e.g., a single wire, a single cable, a single set (e.g., pair) of wires, etc.) connecting control circuit 702 to each of module control circuits 704 of modules 602. Such an implementation may reduce complexity and/or resources compared to an implementation using a plurality of buses to provide a plurality of bias voltages output from control circuit 702, especially for the modular system described herein. While configuration 800 shows three modules 602, any suitable number of modules may be included in configuration 800.

[0077] FIG. 9 illustrates an exemplary circuit 900 that may be an implementation of module control circuit 704. As shown, circuit 900 includes a microprocessor 902 configured to receive a global bias voltage 904 as an input. As described herein, global bias voltage 904 may be generated and provided by a control circuit (e.g., control circuit 702).

[0078] Microprocessor 902 may also include an analog-to-digital converter (ADC) 906 that receives feedback from a detector 908 (e.g., an implementation of detector 606). This feedback may be representative of any suitable property of detector 908 that may affect the generation of global bias voltage 904. ADC 906 may be configured to convert the feedback signal into a digital signal.

[0079] Circuit 900 further includes a digital-to-analog converter (DAC) 910 that receives an output from microprocessor 902. Circuit 900 further includes a step-down circuit 912, which may step down global bias voltage 904 to a detector bias voltage for detector 908. While circuit 900 shows one step-down circuit 912, circuit 900 may further include additional step-down circuits 912 to correspond to a number of detectors on a module (e.g., six total as shown in configuration 700).

[0080] Step-down circuit 912 includes an LDO regulator 914 coupled to resistors 916 (e.g., resistors 916-1 through 916-3) and a capacitor 918. Step-down circuit 912 may be configured to receive global bias voltage 904, which may be a higher voltage

level than an optimal bias voltage level for detector 908 and to step down global bias voltage 904 to a detector bias voltage that corresponds to the optimal bias voltage level. For instance, step-down circuit 912 may receive global bias voltage 904 that is output by control circuit 702 at a voltage level of 14 V. The optimal bias voltage level for detector 908 may be 12 V. Accordingly, LDO regulator 914 may be configured to step down the 14 V input to a 12 V output to provide the detector bias voltage at a voltage level of 12 V for detector 908. Each LDO regulator for each of the other step-down circuits may be appropriately configured to output respective detector bias voltages that correspond to the optimal bias voltage levels for each respective detector.

5 [0081] FIG. 10 shows another exemplary configuration 1000 of components of an optical measurement system (e.g., optical measurement system 100). Configuration 1000 shows module 602-1 (shown in FIG. 6) communicatively coupled to control circuit 702 via communication bus 706. However, rather than including a central module control circuit as in configuration 700 of FIG. 7, each of detectors 606 may directly receive a global bias voltage output by control circuit 702. Each detector 606 may further include a circuit (e.g., a step-down circuit, a step-up circuit, a module control circuit, etc.) configured to step down or step up the global bias voltage to provide a detector bias voltage that is based on an optimal bias voltage level of each detector 606.

10 [0082] For example, control circuit 702 may output a global bias voltage that is 18 V. Detectors 606 may each receive the 18 V global bias voltage. Detector 606-1 may have an optimal bias voltage level of 14.5 V, and therefore may step down the 18 V global bias voltage to output a 14.5 V detector bias voltage to be used in detector 606-1. Detectors 606-2 through 606-6 may similarly step down the 18 V global bias voltage to respective detector bias voltages that correspond to respective optimal bias voltage levels.

15 [0083] As with configuration 700, detectors 606 may measure optimal bias voltage levels in any of the ways described herein so that the stepping down or stepping up of the global bias voltage may be performed and/or adjusted if the optimal bias voltage level changes. Further, detectors 606 may provide the measured optimal bias voltage levels to control circuit 702 so that control circuit 702 may adjust the global bias voltage level based on the optimal bias voltage levels (e.g., a highest optimal bias voltage level).

[0084] Additionally or alternatively, each detector 606 may output a plurality of detector bias voltages, with a different detector bias voltage for groupings of photodetectors of each detector 606. For instance, detector 606-1 may divide the photodetectors on detector 606-1 into quadrants and determine optimal bias voltage levels for each quadrant of photodetectors. Detector 606-1 may then adjust the global bias voltage to output a plurality of detector bias voltages, including a detector bias voltage for each quadrant of photodetectors.

[0085] Additionally or alternatively, while configurations 700, 800, and 1000 show detector bias voltages provided for each detector of each module, in some examples, detector bias voltages may be grouped together. For instance, a module control circuit may output one detector bias voltage for all the detectors of the module. The detector bias voltage may be output at a level based on an average optimal bias voltage level of the detectors of the module, a highest optimal bias voltage level, a lowest optimal bias voltage level, etc. Additionally or alternatively, the module control circuit may group the detectors into two, three, or any other suitable number of groups and output detector bias voltages accordingly. Additionally or alternatively, step-down or step-up circuits may group a plurality of modules together to provide a single detector bias voltage for the detectors of the plurality of modules.

[0086] FIGS. 11-16 illustrate embodiments of a wearable device 1100 that includes elements of the optical detection systems described herein. In particular, the wearable devices 1100 shown in FIGS. 11-16 include a plurality of modules 1102, similar to the modules shown in FIG. 6 as described herein. For example, each module 1102 includes a source 604 and a plurality of detectors 606 (e.g., detectors 606-1 through 606-6). Source 604 may be implemented by one or more light sources similar to light source 110. Each detector 606 may implement or be similar to detector 104 and may include a plurality of photodetectors. The wearable devices 1100 may each also include a controller (e.g., controller 112) and a processor (e.g., processor 108) and/or be communicatively connected to a controller and processor. In general, wearable device 1100 may be implemented by any suitable headgear and/or clothing article configured to be worn by a user. The headgear and/or clothing article may include batteries, cables, and/or other peripherals for the components of the optical measurement systems described herein.

[0087] FIG. 11 illustrates an embodiment of a wearable device 1100 in the form of a helmet with a handle 1104. A cable 1106 extends from the wearable device 1100 for

attachment to a battery or hub (with components such as a processor or the like). FIG. 12 illustrates another embodiment of a wearable device 1100 in the form of a helmet showing a back view. FIG. 13 illustrates a third embodiment of a wearable device 1100 in the form of a helmet with the cable 1106 leading to a wearable garment 1108 (such as a vest or partial vest) that can include a battery or a hub. Alternatively or additionally, the wearable device 1100 can include a crest 1110 or other protrusion for placement of the hub or battery.

[0088] FIG. 14 illustrates another embodiment of a wearable device 1100 in the form of a cap with a wearable garment 1108 in the form of a scarf that may contain or conceal a cable, battery, and/or hub. FIG. 15 illustrates additional embodiments of a wearable device 1100 in the form of a helmet with a one-piece scarf 1108 or two-piece scarf 1108-1. FIG. 16 illustrates an embodiment of a wearable device 1100 that includes a hood 1110 and a beanie 1112 which contains the modules 1102, as well as a wearable garment 1108 that may contain a battery or hub.

[0089] In some examples, a non-transitory computer-readable medium storing computer-readable instructions may be provided in accordance with the principles described herein. The instructions, when executed by a processor of a computing device, may direct the processor and/or computing device to perform one or more operations, including one or more of the operations described herein. Such instructions may be stored and/or transmitted using any of a variety of known computer-readable media.

[0090] A non-transitory computer-readable medium as referred to herein may include any non-transitory storage medium that participates in providing data (e.g., instructions) that may be read and/or executed by a computing device (e.g., by a processor of a computing device). For example, a non-transitory computer-readable medium may include, but is not limited to, any combination of non-volatile storage media and/or volatile storage media. Exemplary non-volatile storage media include, but are not limited to, read-only memory, flash memory, a solid-state drive, a magnetic storage device (e.g. a hard disk, a floppy disk, magnetic tape, etc.), ferroelectric random-access memory ("RAM"), and an optical disc (e.g., a compact disc, a digital video disc, a Blu-ray disc, etc.). Exemplary volatile storage media include, but are not limited to, RAM (e.g., dynamic RAM).

[0091] FIG. 17 illustrates an exemplary computing device 1700 that may be specifically configured to perform one or more of the processes described herein. Any

of the systems, units, computing devices, and/or other components described herein may be implemented by computing device 1700.

[0092] As shown in FIG. 17, computing device 1700 may include a communication interface 1702, a processor 1704, a storage device 1706, and an input/output (“I/O”) module 1708 communicatively connected one to another via a communication infrastructure 1710. While an exemplary computing device 1700 is shown in FIG. 17, the components illustrated in FIG. 17 are not intended to be limiting. Additional or alternative components may be used in other embodiments. Components of computing device 1700 shown in FIG. 17 will now be described in additional detail.

[0093] Communication interface 1702 may be configured to communicate with one or more computing devices. Examples of communication interface 1702 include, without limitation, a wired network interface (such as a network interface card), a wireless network interface (such as a wireless network interface card), a modem, an audio/video connection, and any other suitable interface.

[0094] Processor 1704 generally represents any type or form of processing unit capable of processing data and/or interpreting, executing, and/or directing execution of one or more of the instructions, processes, and/or operations described herein. Processor 1704 may perform operations by executing computer-executable instructions 1712 (e.g., an application, software, code, and/or other executable data instance) stored in storage device 1706.

[0095] Storage device 1706 may include one or more data storage media, devices, or configurations and may employ any type, form, and combination of data storage media and/or device. For example, storage device 1706 may include, but is not limited to, any combination of the non-volatile media and/or volatile media described herein.

Electronic data, including data described herein, may be temporarily and/or permanently stored in storage device 1706. For example, data representative of computer-executable instructions 1712 configured to direct processor 1704 to perform any of the operations described herein may be stored within storage device 1706. In some examples, data may be arranged in one or more databases residing within storage device 1706.

[0096] I/O module 1708 may include one or more I/O modules configured to receive user input and provide user output. I/O module 1708 may include any hardware, firmware, software, or combination thereof supportive of input and output capabilities. For example, I/O module 1708 may include hardware and/or software for capturing user

input, including, but not limited to, a keyboard or keypad, a touchscreen component (e.g., touchscreen display), a receiver (e.g., an RF or infrared receiver), motion sensors, and/or one or more input buttons.

5 **[0097]** I/O module 1708 may include one or more devices for presenting output to a user, including, but not limited to, a graphics engine, a display (e.g., a display screen), one or more output drivers (e.g., display drivers), one or more audio speakers, and one or more audio drivers. In certain embodiments, I/O module 1708 is configured to provide graphical data to a display for presentation to a user. The graphical data may be representative of one or more graphical user interfaces and/or any other graphical
10 content as may serve a particular implementation.

[0098] FIG. 18 illustrates an exemplary method 1800 that may be performed by module control circuit 704 and/or any implementation thereof. While FIG. 18 illustrates exemplary operations according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the operations shown in FIG. 18. Each of the
15 operations shown in FIG. 18 may be performed, or repeated as needed for each respective module located in its respective slot on the wearable device, in any of the ways described herein.

[0099] In operation 1802, a module control circuit of an optical measurement system receives a global bias voltage from a control circuit of the optical measurement system.

20 **[0100]** In operation 1804, the module control circuit outputs a plurality of detector bias voltages based on the global bias voltage and including a respective detector bias voltage for each detector of a plurality of detectors of the module, the plurality of detectors configured to detect arrival times for photons of light after the light is scattered by a target within a body.

25 **[0101]** An exemplary optical measurement system described herein includes a control circuit configured to output a global bias voltage and a module communicatively coupled to the control circuit. The module includes a light source configured to emit light directed at a target. The module further includes a plurality of detectors configured to detect arrival times for photons of the light after the light is scattered by the target. The
30 module further includes a module control circuit configured to receive the global bias voltage and output a plurality of detector bias voltages based on the global bias voltage. The plurality of detector bias voltages include a respective detector bias voltage for each detector of the plurality of detectors.

[0102] An exemplary wearable system described herein includes a control circuit configured to output a global bias voltage. The wearable system further includes a head-mountable component configured to be attached to a head of the user, the head-mountable component including a module communicatively coupled to the control
5 circuit. The module includes a light source configured to emit light directed at a target. The module further includes a plurality of detectors configured to detect arrival times for photons of the light after the light is scattered by the target. The module further includes a module control circuit configured to receive the global bias voltage and output a plurality of detector bias voltages based on the global bias voltage. The plurality of
10 detector bias voltages include a respective detector bias voltage for each detector of the plurality of detectors.

[0103] An exemplary method described herein includes receiving, by a module control circuit of a module of an optical measurement system, a global bias voltage from a control circuit of the optical measurement system. The method further includes
15 outputting, by the module control circuit, a plurality of detector bias voltages based on the global bias voltage and including a respective detector bias voltage for each detector of a plurality of detectors of the module, the plurality of detectors configured to detect arrival times for photons of light after the light is scattered by a target within a body.

[0104] In the preceding description, various exemplary embodiments have been described with reference to the accompanying drawings. It will, however, be evident that various modifications and changes may be made thereto, and additional
20 embodiments may be implemented, without departing from the scope of the invention as set forth in the claims that follow. For example, certain features of one embodiment described herein may be combined with or substituted for features of another
25 embodiment described herein. The description and drawings are accordingly to be regarded in an illustrative rather than a restrictive sense.

CLAIMS

What is claimed is:

- 5 1. An optical measurement system comprising:
a control circuit configured to output a global bias voltage; and
a module communicatively coupled to the control circuit, the module comprising:
a light source configured to emit light directed at a target,
a plurality of detectors configured to detect arrival times for photons of the
10 light after the light is scattered by the target, and
a module control circuit configured to:
receive the global bias voltage, and
output a plurality of detector bias voltages based on the global bias
voltage and including a respective detector bias voltage for each detector of the
15 plurality of detectors.
2. The optical measurement system of claim 1, wherein:
the module control circuit is further configured to measure a respective optimal
detector bias voltage for each detector of the plurality of detectors; and
20 the outputting the plurality of detector bias voltages is further based on the
respective optimal detector bias voltage for each detector.
3. The optical measurement system of claim 1, wherein:
the global bias voltage is a voltage level higher than the plurality of detector bias
25 voltages; and
the outputting the plurality of detector bias voltages comprises stepping down the
global bias voltage for each respective detector bias voltage.
4. The optical measurement system of claim 3, wherein the control circuit is
30 further configured to:
monitor the plurality of detector bias voltages; and
adjust, based on a highest voltage level of the plurality of detector bias voltages,
the global bias voltage.

5. The optical measurement system of claim 4, wherein:

the module control circuit is further configured to measure a respective optimal detector bias voltage for each detector of the plurality of detectors; and

5 the monitoring the plurality of detector bias voltages comprises receiving, from the module control circuit, the highest voltage level of the plurality of detector bias voltages based on the respective optimal detector bias voltage for each detector.

6. The optical measurement system of claim 1, wherein:

10 the global bias voltage is a voltage level lower than the plurality of detector bias voltages; and

the outputting the plurality of detector bias voltages comprises stepping up the global bias voltage for each respective detector bias voltage.

15 7. The optical measurement system of claim 6, wherein the module control circuit comprises a charge pump configured to step up the global bias voltage.

8. The optical measurement system of claim 1, further comprising an additional module communicatively coupled to the control circuit, the additional module
20 comprising:

an additional light source configured to emit additional light directed at the target,

an additional plurality of detectors configured to detect arrival times for photons of the additional light after the additional light is scattered by the target, and

an additional module control circuit configured to:

25 receive the global bias voltage, and

output an additional plurality of detector bias voltages based on the global bias voltage and including a respective detector bias voltage for each detector of the additional plurality of detectors.

30 9. The optical measurement system of claim 8, wherein the control circuit is configured to output the global bias voltage to the module control circuit and the additional module control circuit via a single communication bus.

10. The optical measurement system of claim 1, wherein each detector comprises a plurality of photodetectors.

5 11. The optical measurement system of claim 10, wherein each photodetector comprises:
a single photon avalanche diode (SPAD); and
a fast gating circuit configured to arm and disarm the SPAD.

10 12. The optical measurement system of claim 1, further comprising a wearable device configured to be worn by a user, wherein:
the wearable device includes the module; and
the target includes tissue within the user.

15 13. The optical measurement system of claim 12, wherein the wearable device includes a head-mountable component configured to be worn on a head of a user.

20 14. A wearable system for use by a user comprising:
a control circuit configured to output a global bias voltage; and
a head-mountable component configured to be attached to a head of the user, the head-mountable component comprising a module communicatively coupled to the control circuit, the module comprising:
a light source configured to emit light directed at a target,
a plurality of detectors configured to detect arrival times for photons of the
25 light after the light is scattered by the target, and
a module control circuit configured to:
receive the global bias voltage, and
output a plurality of detector bias voltages based on the global bias voltage and including a respective detector bias voltage for each detector of the
30 plurality of detectors.

15. The wearable system of claim 14, wherein:
the module control circuit is further configured to measure a respective optimal detector bias voltage for each detector of the plurality of detectors; and

the outputting the plurality of detector bias voltages is further based on the respective optimal detector bias voltage for each detector.

16. The wearable system of claim 14, wherein:

5 the global bias voltage is a voltage level higher than the plurality of detector bias voltages; and

the outputting the plurality of detector bias voltages comprises stepping down the global bias voltage for each respective detector bias voltage.

10 17. The wearable system of claim 16, wherein the control circuit is further configured to:

monitor the plurality of detector bias voltages; and

adjust, based on a highest voltage level of the plurality of detector bias voltages, the global bias voltage.

15

18. The wearable system of claim 17, wherein:

the module control circuit is further configured to measure a respective optimal detector bias voltage for each detector of the plurality of detectors; and

20 the monitoring the plurality of detector bias voltages comprises receiving, from the module control circuit, the highest voltage level of the plurality of detector bias voltages based on the respective optimal detector bias voltage for each detector.

19. The wearable system of claim 14, wherein:

25 the global bias voltage is a voltage level lower than the plurality of detector bias voltages; and

the outputting the plurality of detector bias voltages comprises stepping up the global bias voltage for each respective detector bias voltage.

30 20. The wearable system of claim 19, wherein the module control circuit comprises a charge pump configured to step up the global bias voltage.

21. The wearable system of claim 14, wherein the head-mountable component further comprises an additional module communicatively coupled to the control circuit, the additional module comprising:

an additional light source configured to emit additional light directed at the target,
an additional plurality of detectors configured to detect arrival times for photons
of the additional light after the additional light is scattered by the target, and

an additional module control circuit configured to:

- 5 receive the global bias voltage, and
 output an additional plurality of detector bias voltages based on the global
bias voltage and including a respective detector bias voltage for each detector of the
additional plurality of detectors.

10 22. The wearable system of claim 21, wherein the control circuit is configured
to output the global bias voltage to the module control circuit and the additional module
control circuit via a single communication bus.

15 23. The wearable system of claim 14, wherein each detector comprises a
plurality of photodetectors.

20 24. The wearable system of claim 23, wherein each photodetector comprises:
a single photon avalanche diode (SPAD); and
a fast gating circuit configured to arm and disarm the SPAD.

25 25. The wearable system of claim 14, wherein the control circuit is housed in
the head-mountable component.

26 26. A method comprising:
25 receiving, by a module control circuit of a module of an optical measurement
system, a global bias voltage from a control circuit of the optical measurement system;
and

30 outputting, by the module control circuit, a plurality of detector bias voltages
based on the global bias voltage and including a respective detector bias voltage for
each detector of a plurality of detectors of the module, the plurality of detectors
configured to detect arrival times for photons of light after the light is scattered by a
target within a body.

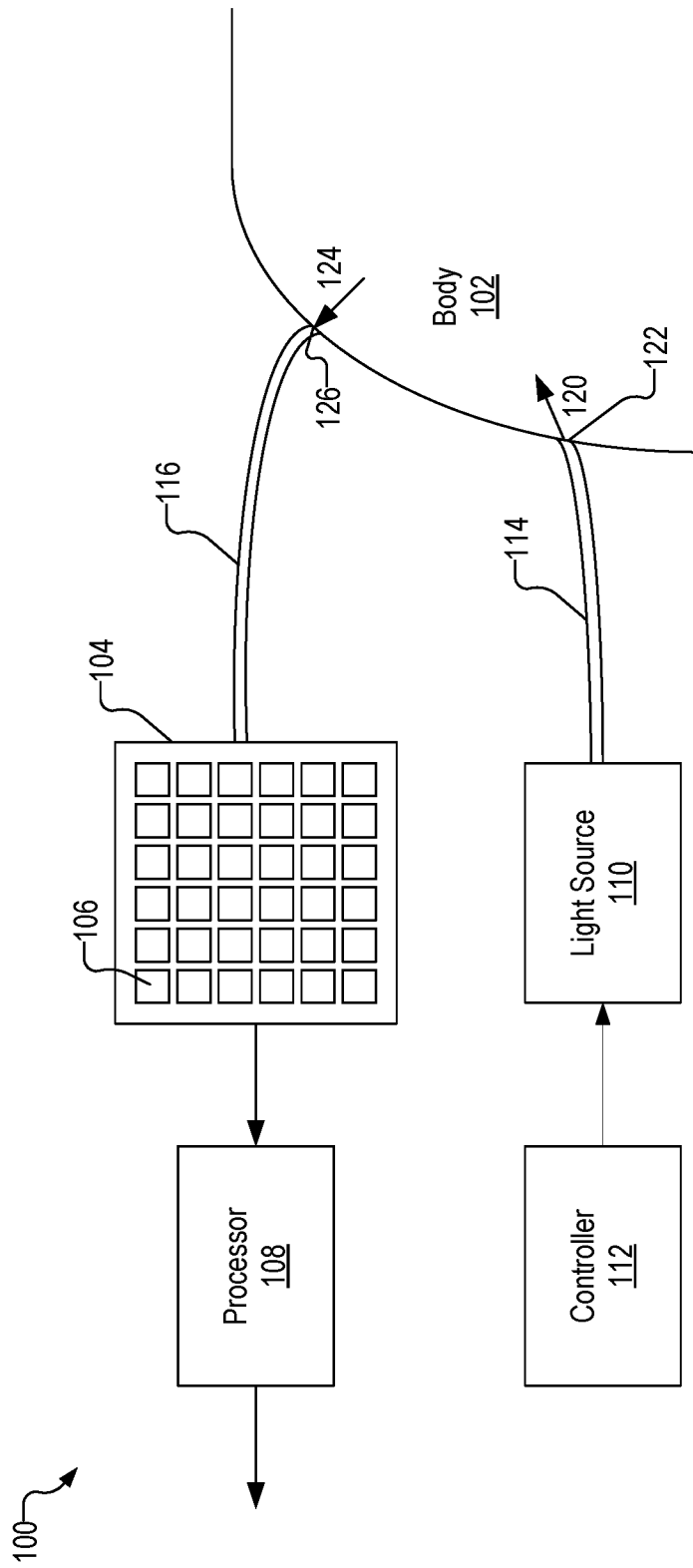


Fig. 1

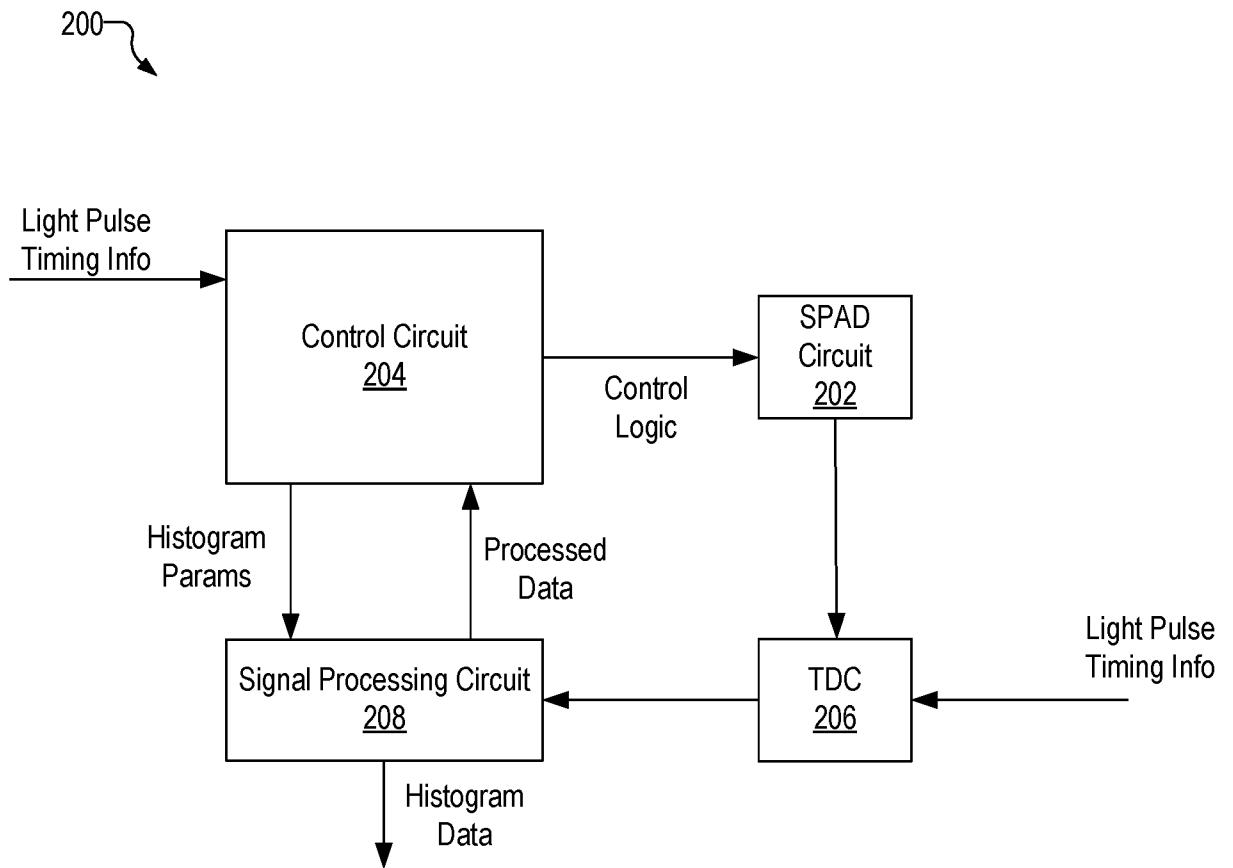


Fig. 2

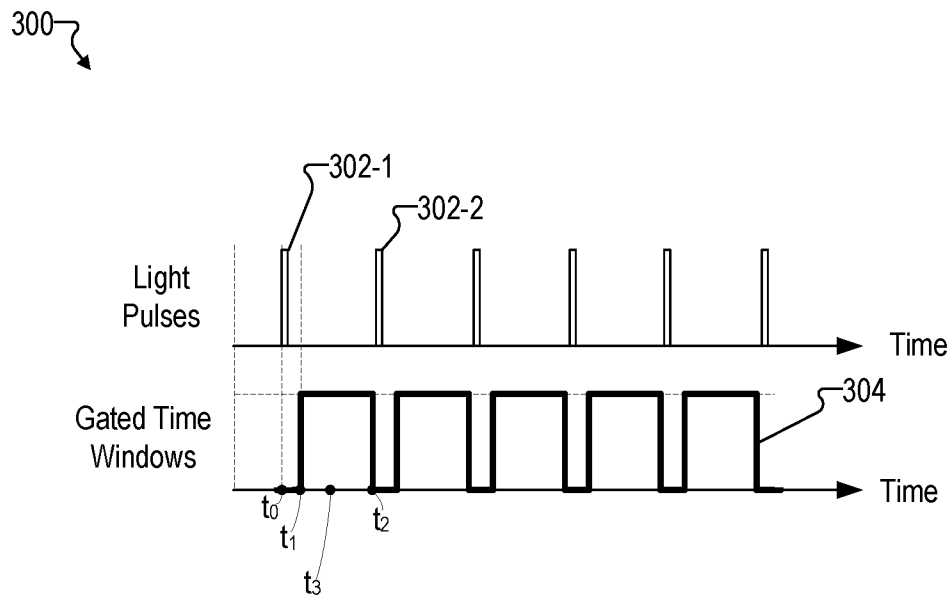


Fig. 3

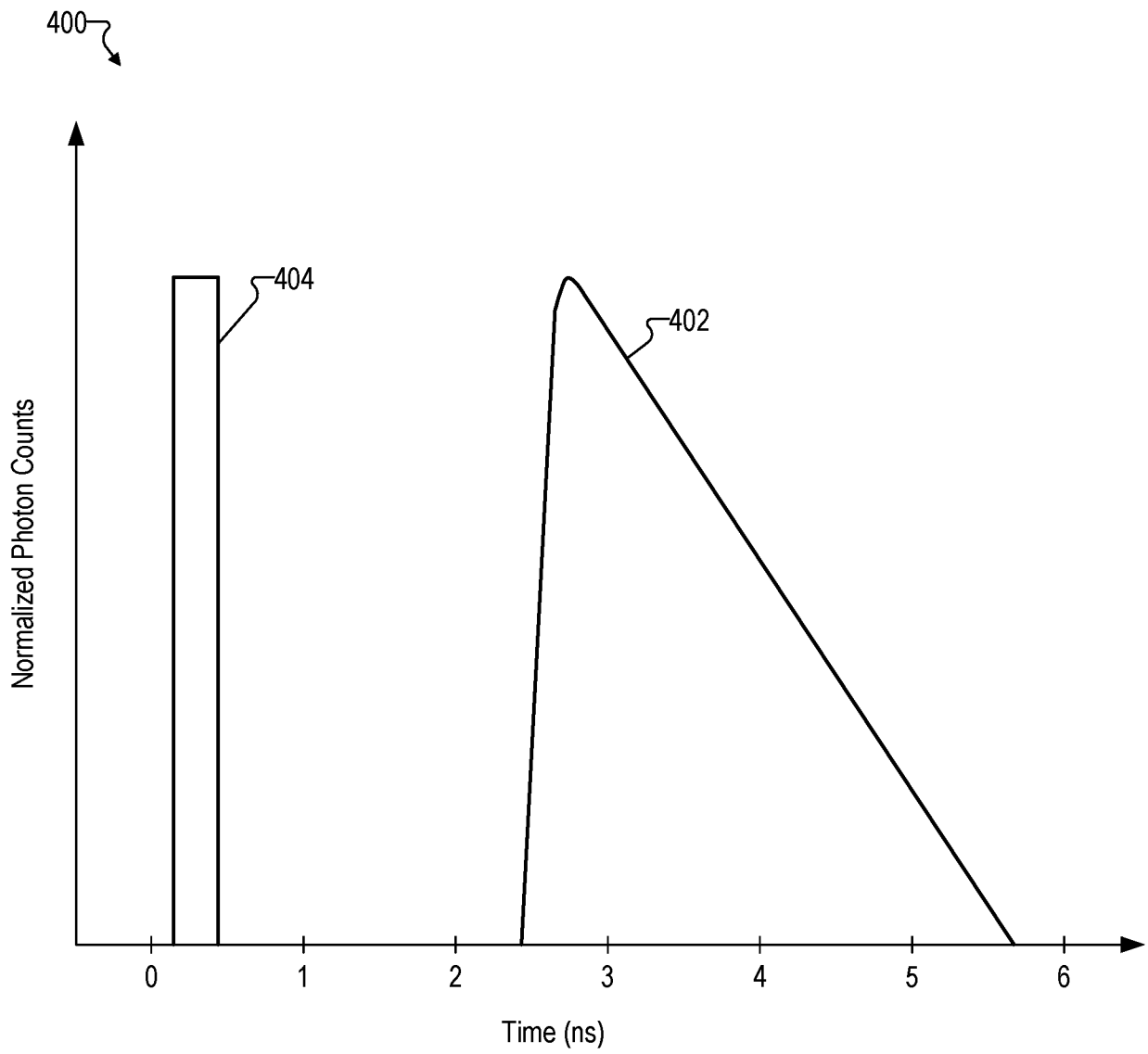


Fig. 4

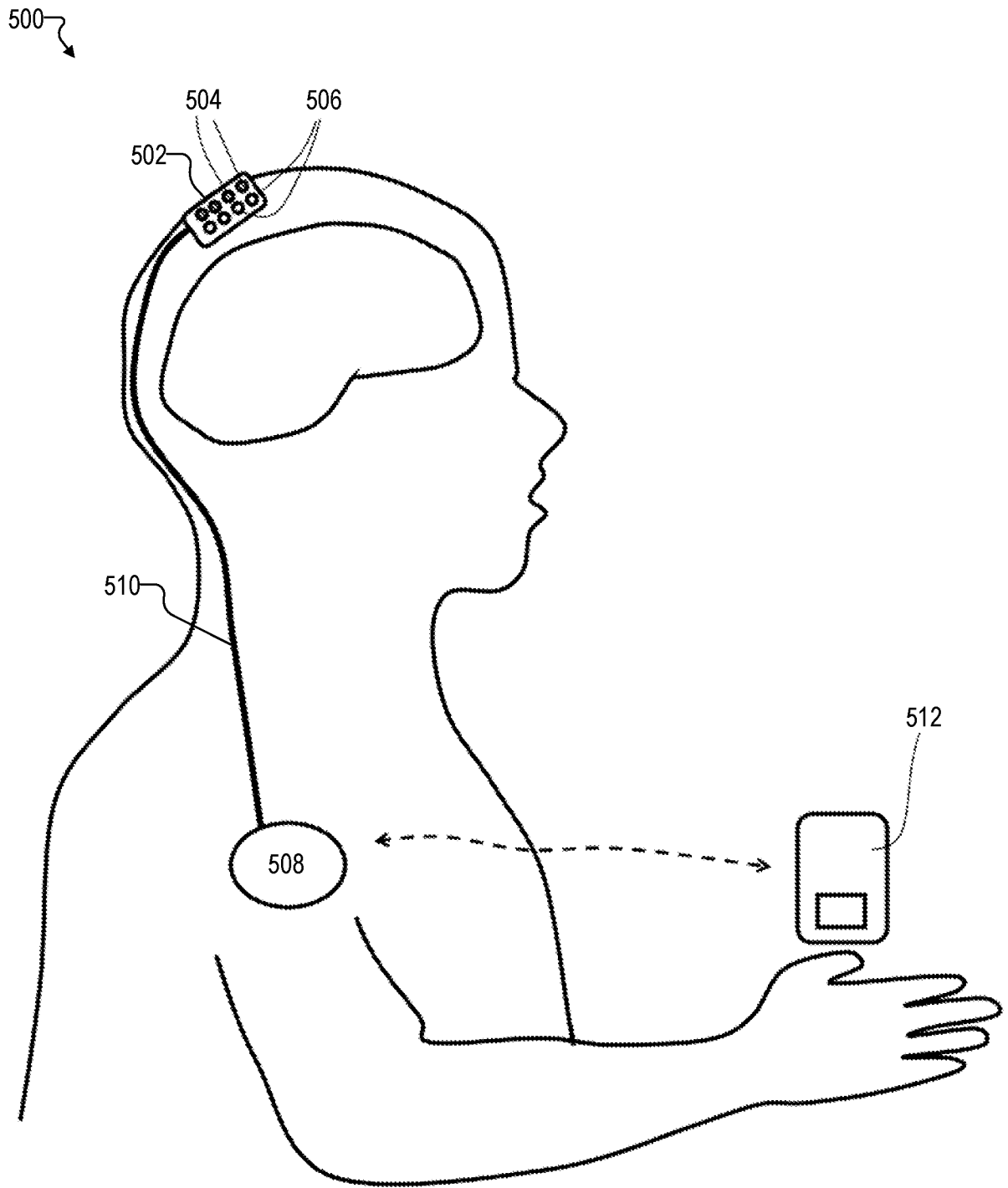


Fig. 5

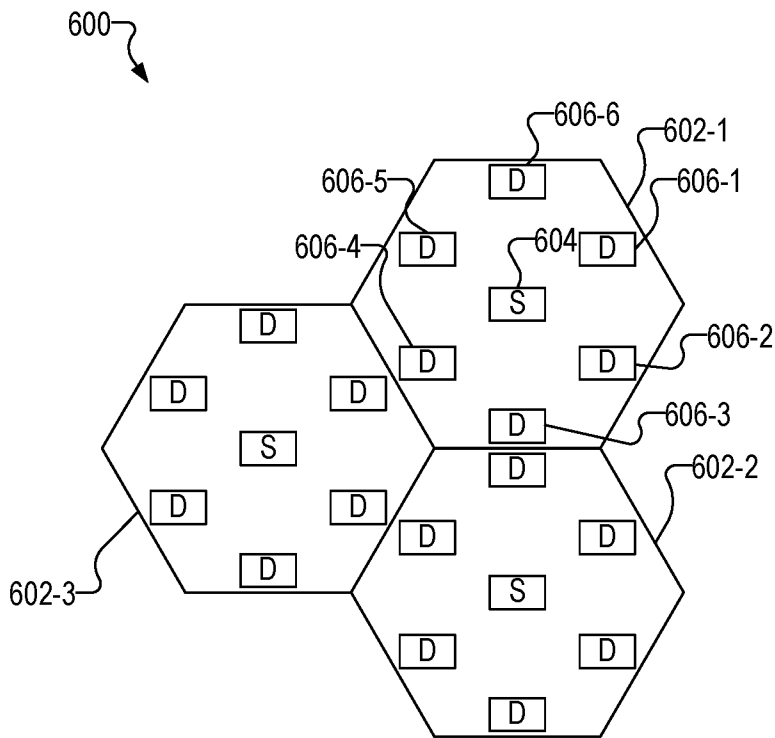


Fig. 6

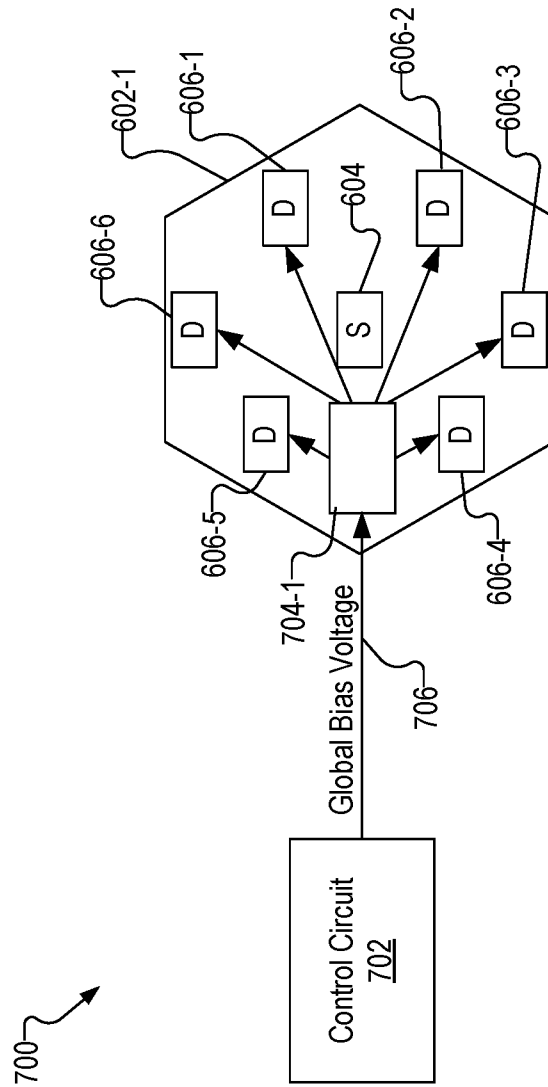


Fig. 7

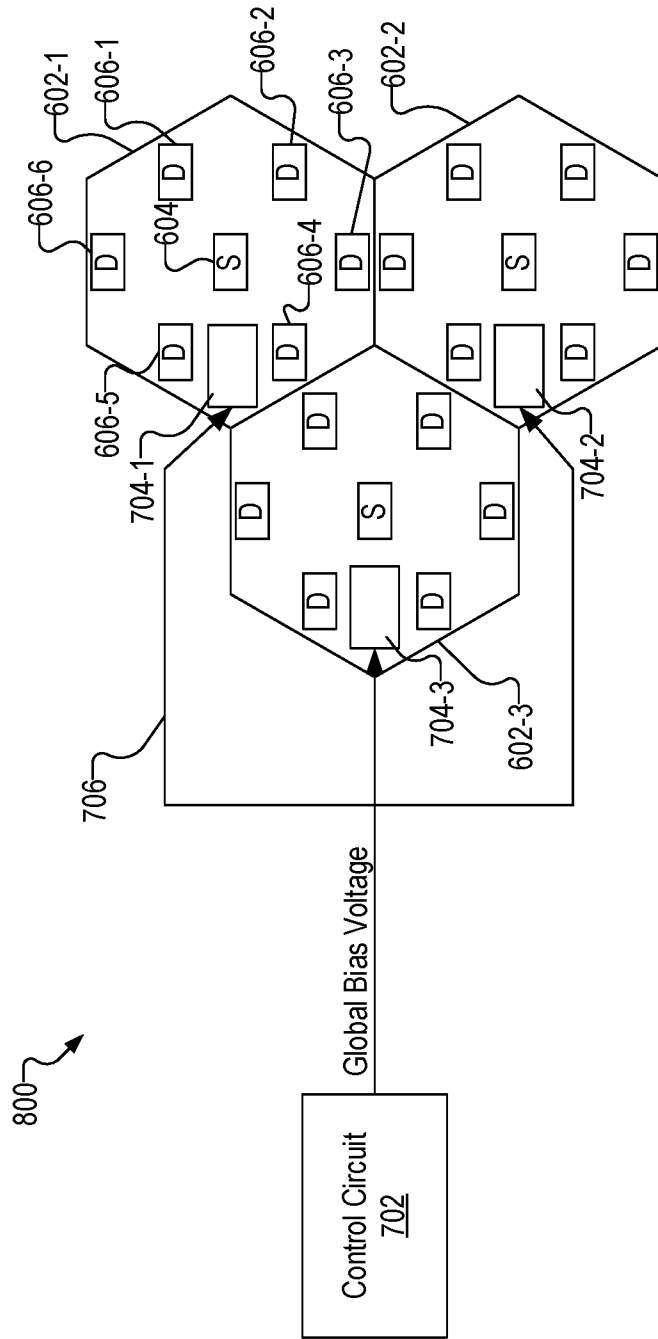


Fig. 8

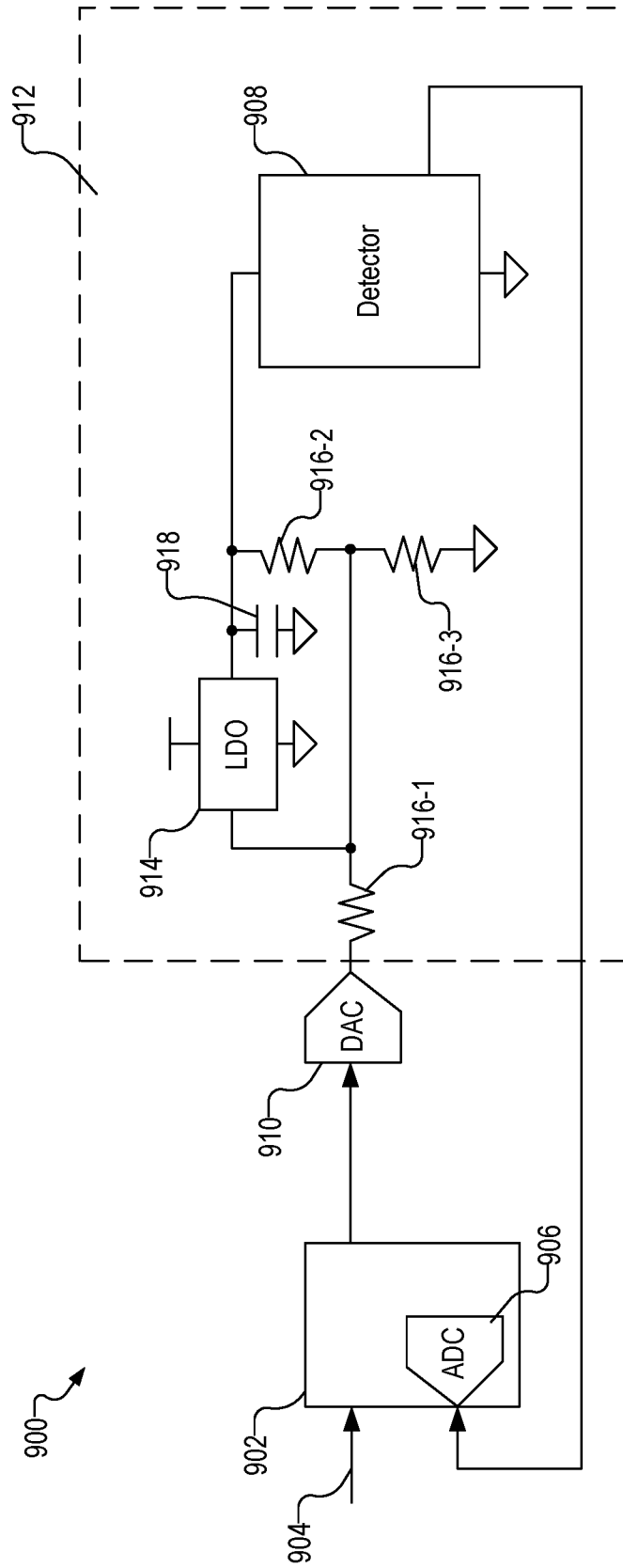


Fig. 9

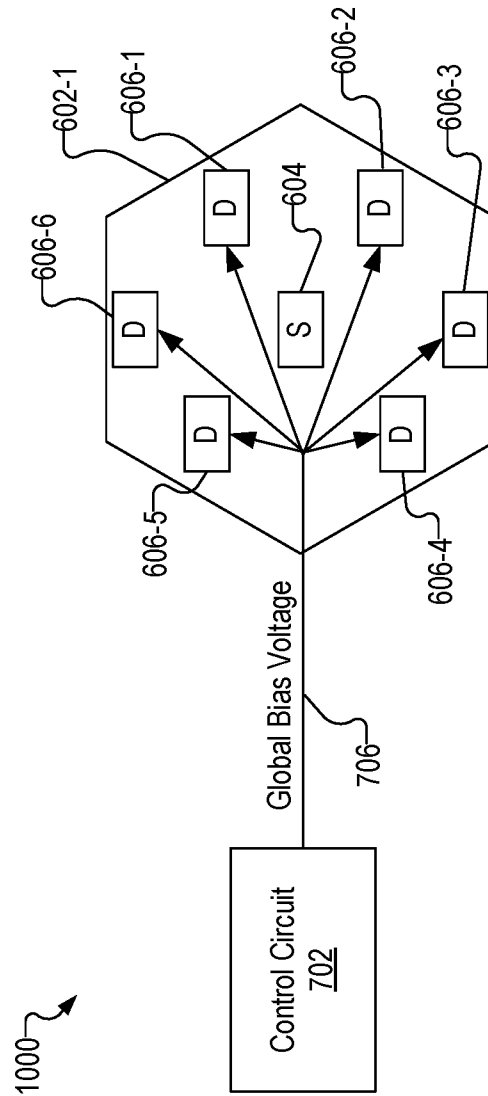


Fig. 10

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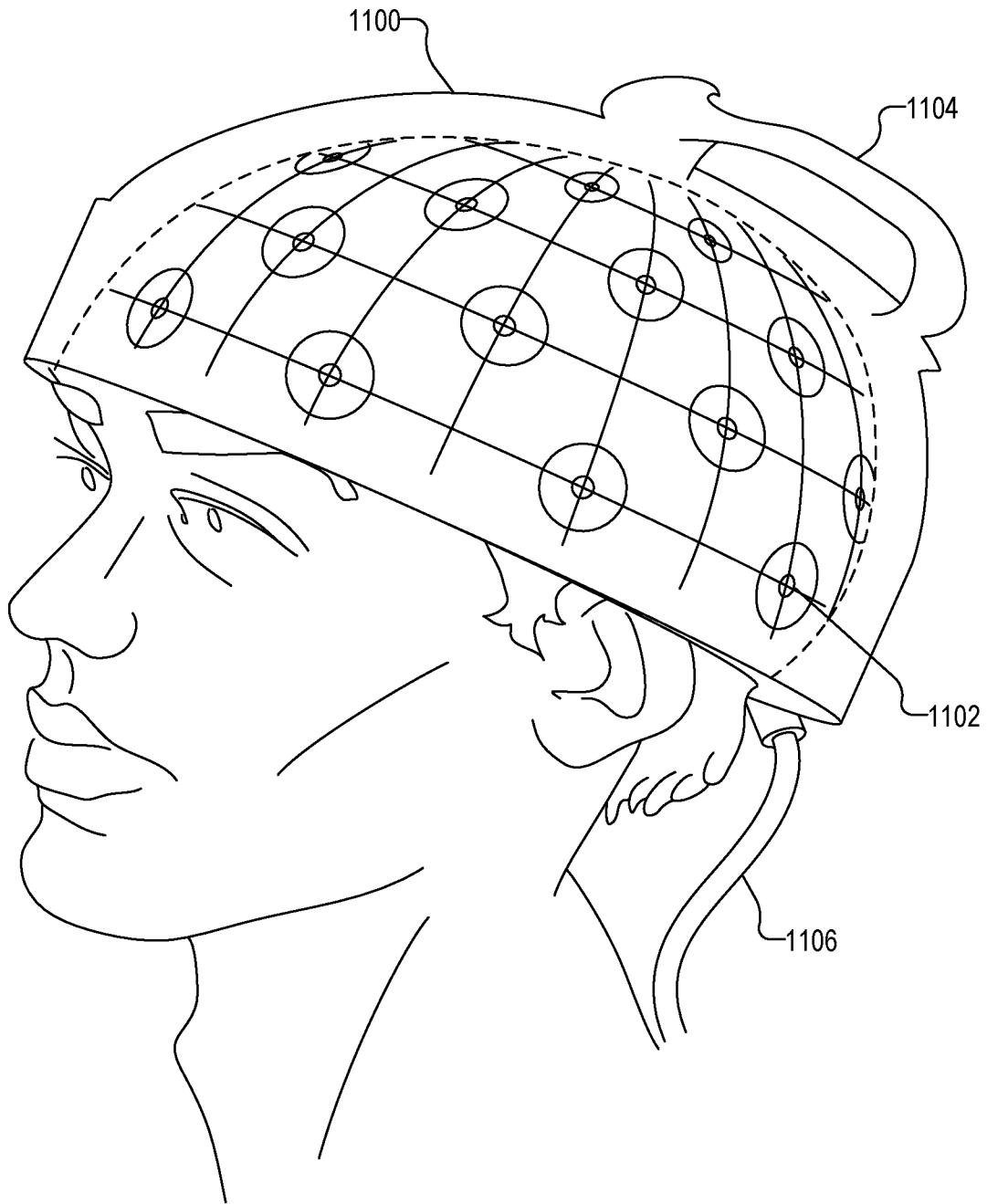


Fig. 11

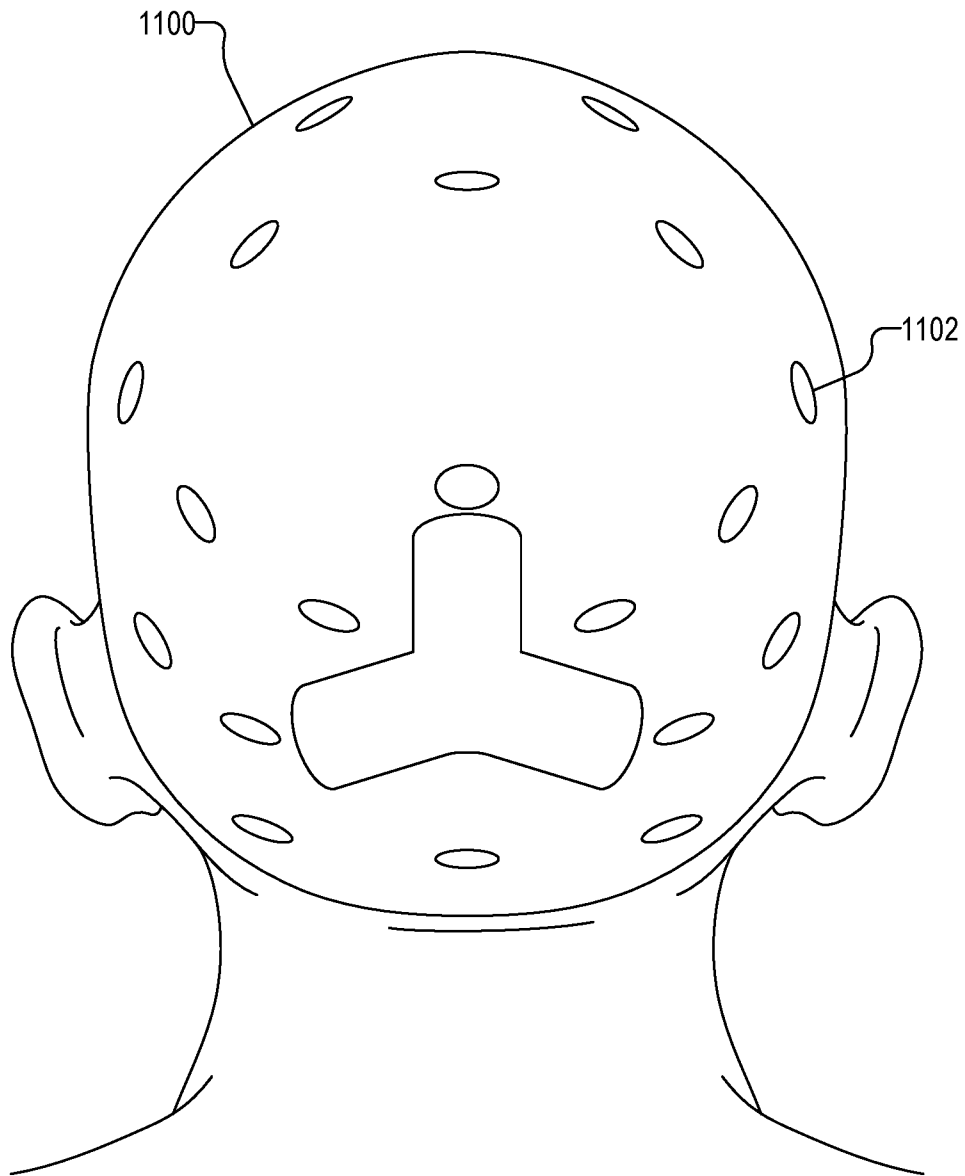


Fig. 12

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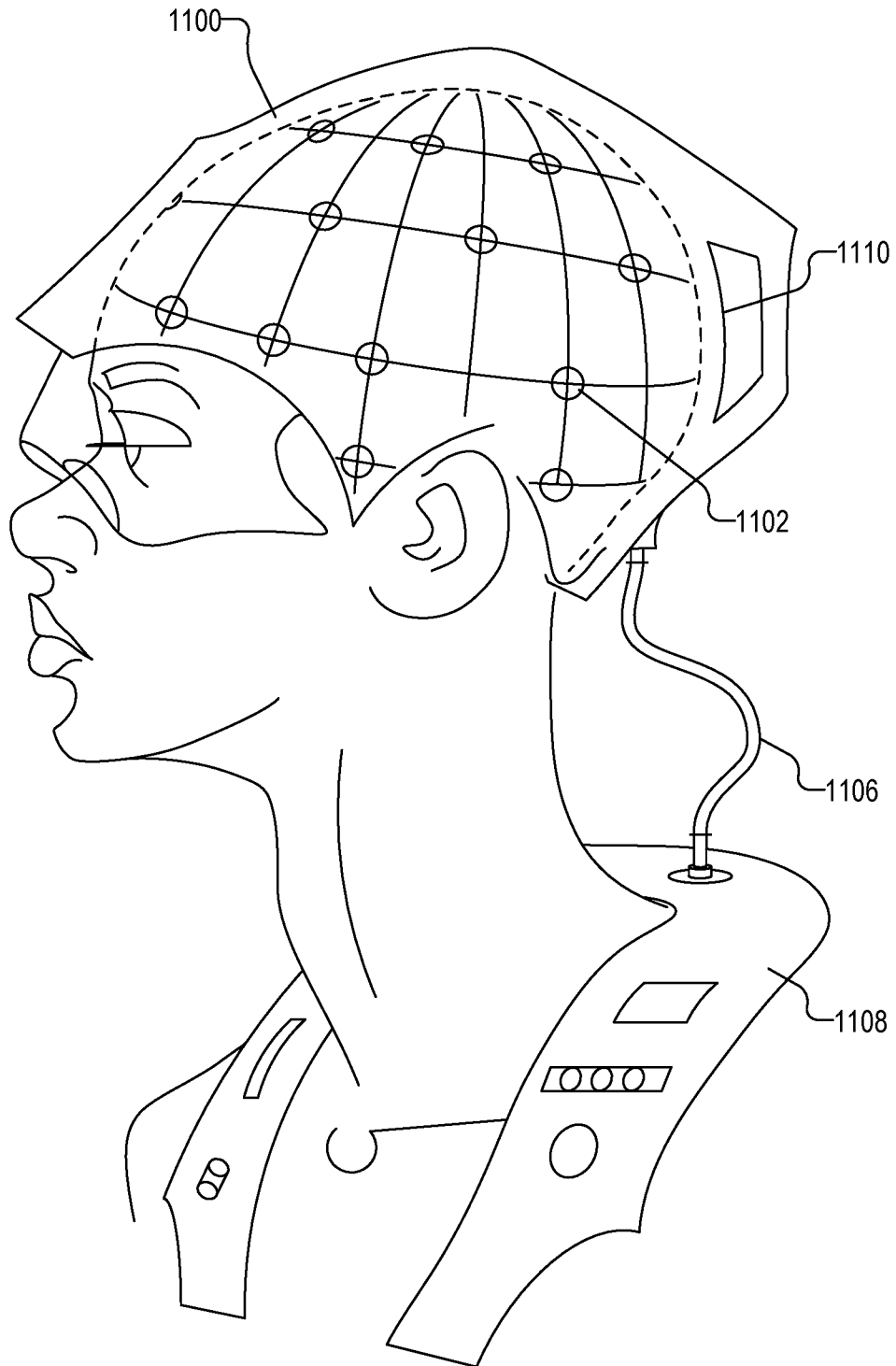


Fig. 13

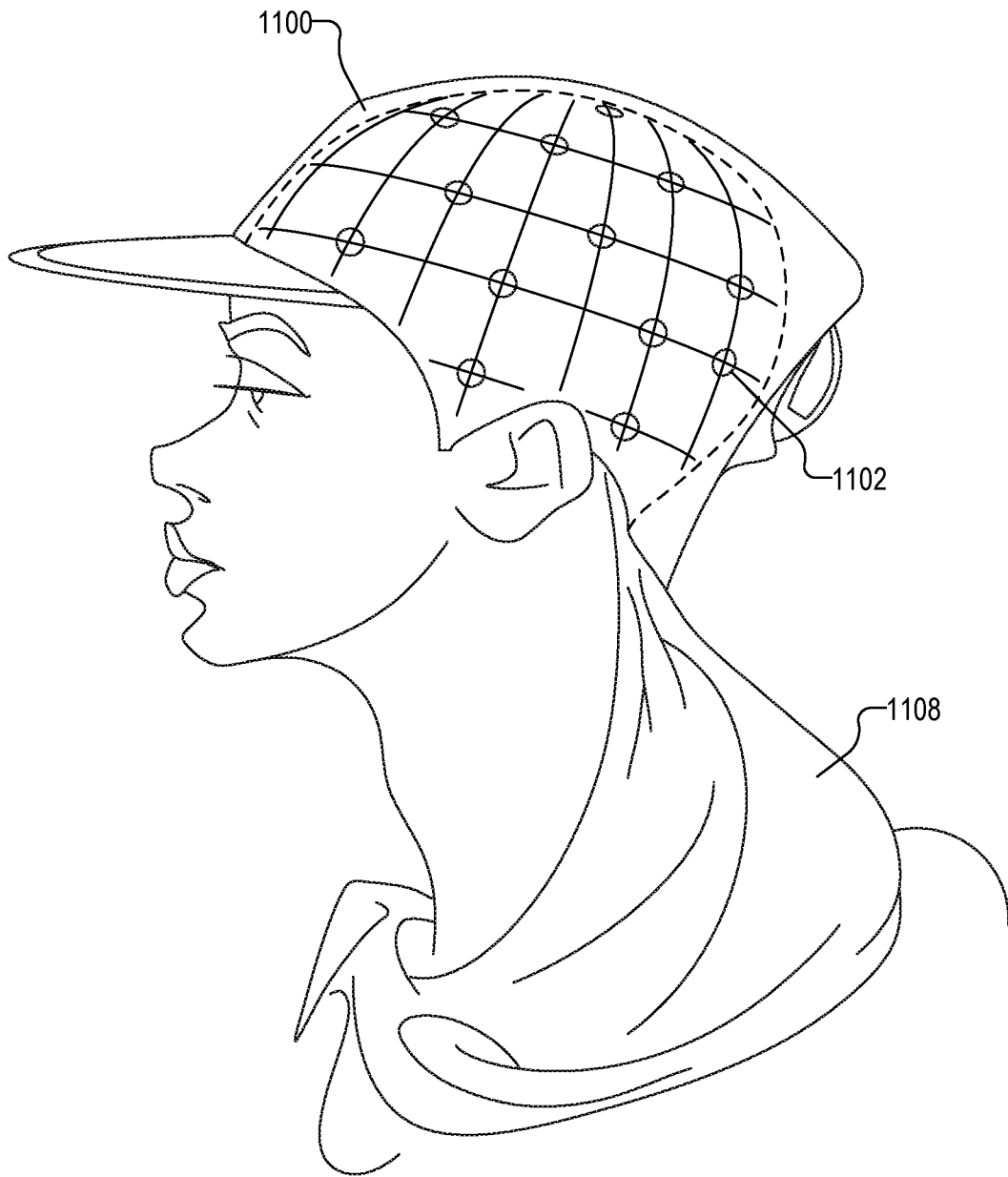


Fig. 14

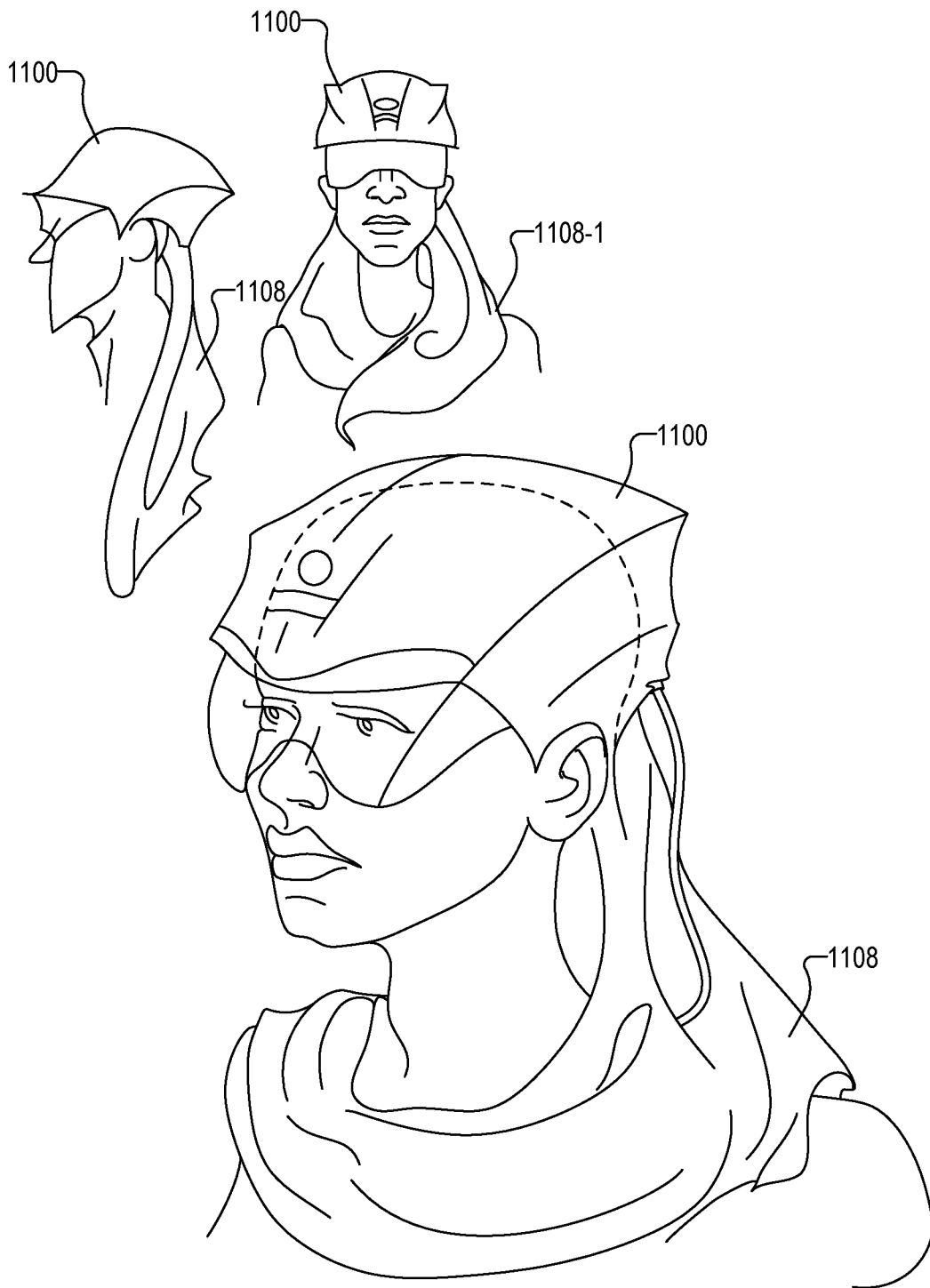


Fig. 15

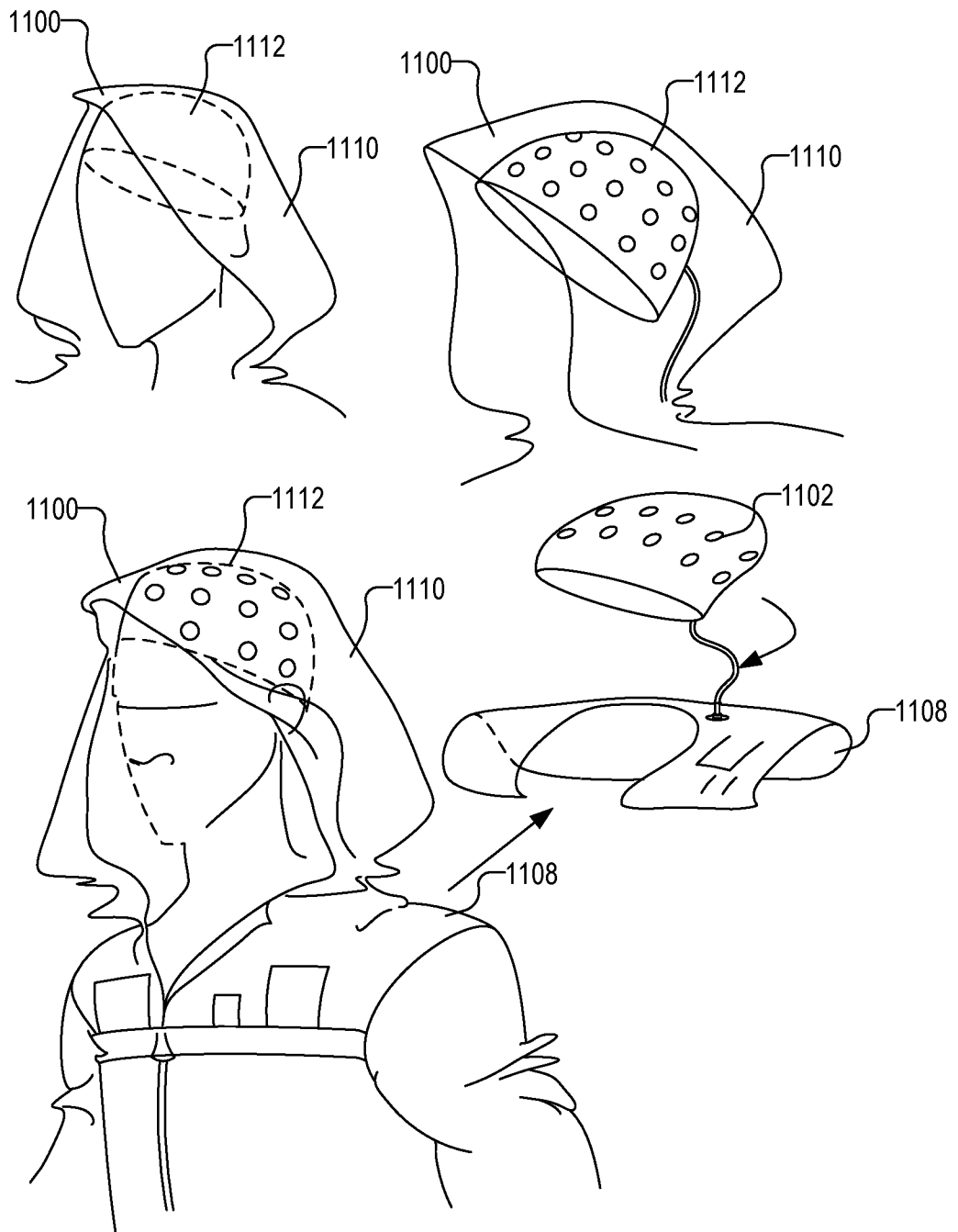


Fig. 16

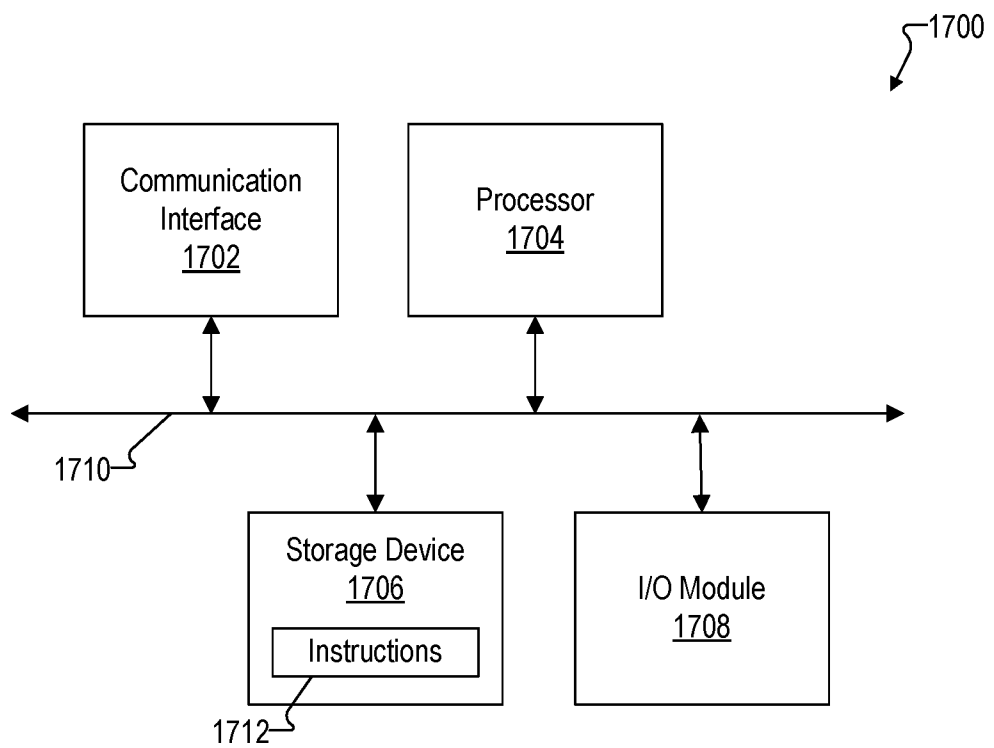


Fig. 17

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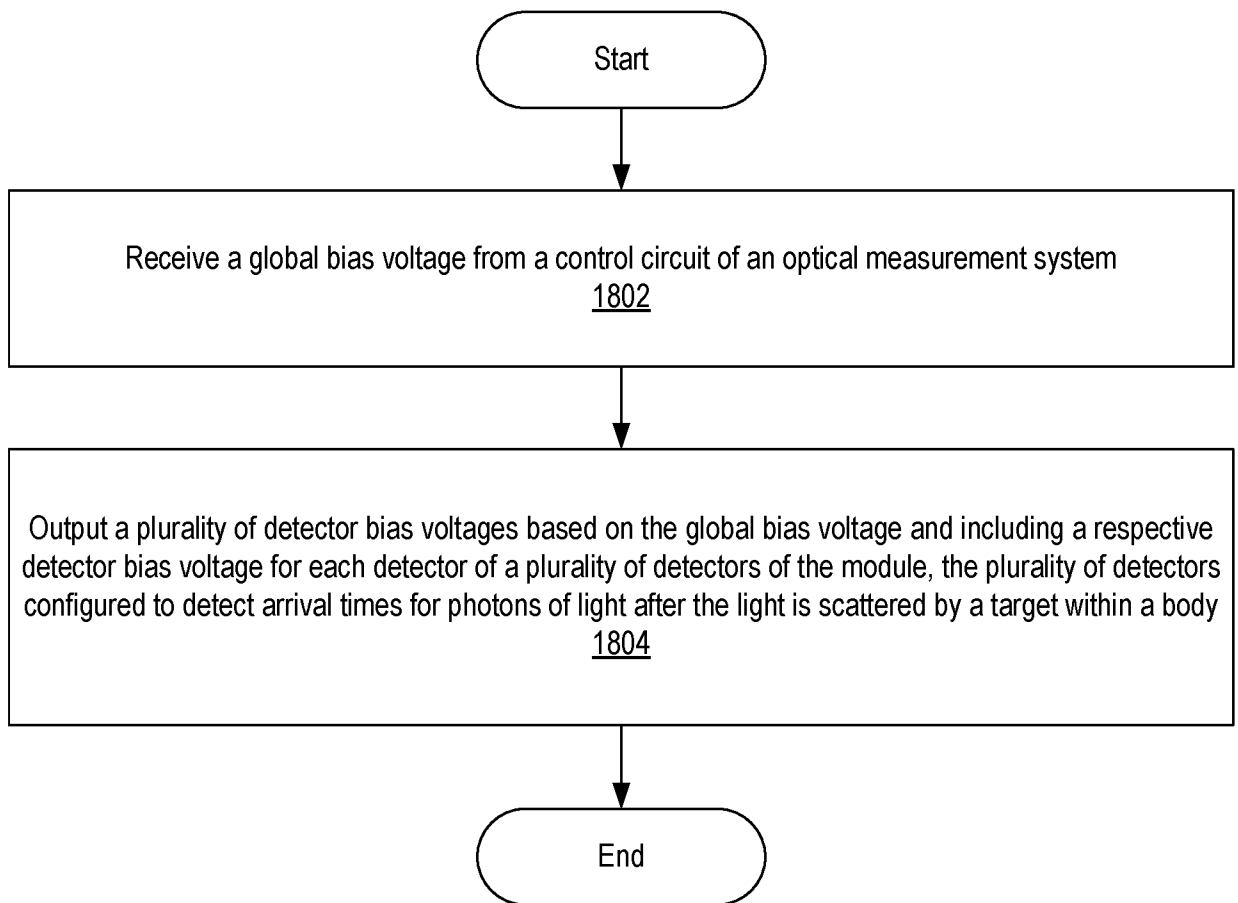


Fig. 18

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/022487

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/00 G01S7/4861 G01S17/02 H01L31/107
ADD.
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)
A61B G01S H01L
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A Y	US 2017/176579 A1 (NICLASS CRISTIANO L [US] ET AL) 22 June 2017 (2017-06-22) paragraphs [0006], [0028], [0045], [0048] - [0049]; figures 1,2,3 ----- WO 2019/221784 A1 (HI LLC [US]) 21 November 2019 (2019-11-21) paragraphs [0028], [0029], [0046], [0060] - [0065], [0127], [0130]; figures 1-23 ----- -/--	1,10,11, 26 2-9, 12-25 1-26

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	"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
"E" earlier application or patent but published on or after the international filing date	"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
"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)	"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
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search 3 June 2021	Date of mailing of the international search report 17/06/2021
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Hirsch, Arthur
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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/022487

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ZHENG LIXIA ET AL: "An Integrated Bias Voltage Control Method for SPAD Arrays", IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 30, no. 19, 1 October 2018 (2018-10-01), pages 1723-1726, XP011690239, ISSN: 1041-1135, DOI: 10.1109/LPT.2018.2867537 [retrieved on 2018-09-13]	26
Y	Abstract; page 1723, column 1 - page 1724, column 2; figures 1-9	1-26
X	----- US 2017/179173 A1 (MANDAI SHINGO [US] ET AL) 22 June 2017 (2017-06-22)	26
A	paragraphs [0005], [0006], [0026], [3637]; figures 1-7	1-25
A	----- CHANG PO-HSUAN ET AL: "Constant Excess Bias Control for Single-Photon Avalanche Diode Using Real-Time Breakdown Monitoring", IEEE ELECTRON DEVICE LETTERS, IEEE, USA, vol. 36, no. 8, 1 August 2015 (2015-08-01), pages 859-861, XP011663974, ISSN: 0741-3106, DOI: 10.1109/LED.2015.2450936 [retrieved on 2015-07-22] abstract, Proposed design; page 860 - page 861	1-26
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International application No

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