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STRUCTURED POLARIZATION-BASED EYE TRACKING

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STRUCTURED POLARIZATION-BASED EYE TRACKING

TECHNOLOGICAL FIELD

[0001] Exemplary embodiments of this disclosure relate generally to methods, apparatuses, and computer program products for providing structured polarization-based eye tracking for artificial reality devices.

BACKGROUND

[0002] Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, for example, a virtual reality, an augmented reality, a mixed reality, a hybrid reality, or some combination or derivative thereof. Artificial reality content may include completely computer-generated content or computer-generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, haptic feedback, or some combination thereof, any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional (3D) effect to the viewer). Additionally, in some instances, artificial reality may be associated with applications, products, accessories, services, or some combination thereof, that may be used to, for example, create content in an artificial reality or are otherwise used in (e.g., to perform activities in) an artificial reality. Head-mounted displays (HMDs) including one or more near-eye displays may often be used to present visual content to a user for use in artificial reality applications.

[0003] Eye tracking systems may aim for high-resolution measurement and tracking of eye position (e.g., pupil position). Some camera-based imaging systems that may be used in eye tracking may be enhanced to include depth sensing when used in combination with structured illumination. However, depth sensing may have some limitations and in particular eye rotation may be unable to be easily captured due to a centrosymmetric nature of eyes. Also, due to some practical limitations of structured illumination imaging, the direction of an eye gaze may be unable to be reliably captured with sufficient accuracy for full eye tracking with desired resolution.

[0004] In view of the foregoing drawbacks, it may be beneficial to provide structured polarization to facilitate an efficient and reliable mechanism for capturing eye movement, eye rotation, gaze direction, and pupil position for eye tracking purposes.

BRIEF SUMMARY

[0005] Exemplary embodiments are described for an eye tracking system which may be associated with illumination patterns with uniform intensity and structured polarization states for artificial reality devices or HMDs. The eye-tracking system may include a polarization-sensitive camera that may detect changes in polarization states, degrees of linear polarization, or angles of polarization associated with captured reflections of illuminated light.

[0006] The exemplary embodiments may utilize illumination patterns with uniform intensity, and structured (e.g., spatially varying) polarization states for capturing or determining several types of information that may be beneficial for eye tracking purposes.

[0007] For instance, the exemplary embodiments may determine intensity information, polarization information and depth information, based on the polarization states, which may be useful for eye tracking. The exemplary embodiments may provide a mechanism for capturing or determining the information, associated with polarization states, at the same time (e.g., in a single image capture) utilizing a single sensor such as, for example, a polarization-sensitive camera and by utilizing this information may infer or determine one or more parameters such as, for example, eye rotation, gaze direction or pupil position that may be useful for eye tracking purposes. By combining these parameters that may be captured or determined based on an image capture of an eye(s) (e.g., a single image capture of an eye(s)) and considering the parameters (e.g., together or separately) may allow the exemplary embodiments to improve performance of the eye tracking systems of the exemplary embodiments.

[0008] In an example, a system may include a waveguide having a front and a rear surface. The waveguide may be associated with a display and may be arranged to guide light onto an eye of a user to make an image visible to the user. The light may be guided or propagated through the waveguide. The system may include a polarization-sensitive camera that may detect one or more changes in polarization states, degrees of linear polarization, and angles of polarization associated with captured reflections of illuminated light.

[0009] Additional advantages will be set forth in part in the description which follows or may be learned by practice. The advantages will be realized and attained by means of the elements and combinations particularly pointed out in the appended claims. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The summary, as well as the following detailed description, is further understood when read in conjunction with the appended drawings. For the purpose of illustrating the disclosed subject matter, there are shown in the drawings exemplary embodiments of the disclosed subject matter; however, the disclosed subject matter is not limited to the specific methods, compositions, and devices disclosed. In addition, the drawings are not necessarily drawn to scale. In the drawings:

[0011] FIG. 1 illustrates an example head-mounted display associated with artificial reality content.

[0012] FIG. 2 illustrates a block diagram of an exemplary hardware or software architecture in accordance with an exemplary embodiment.

[0013] FIG. 3 illustrates an exemplary zoomed plane view of the head-mounted display that includes a waveguide and a polarization-sensitive camera taken at dashed circle A of FIG. 1 in accordance with an exemplary embodiment.

[0014] FIG. 4 illustrates an exemplary zoomed side view of the head-mounted display in accordance with an exemplary embodiment.

[0015] FIG. 5 illustrates an example of structured polarization according to an exemplary embodiment.

[0016] FIG. 6 illustrates how a polarization-sensitive camera may detect reflected structured polarized light in accordance with an exemplary embodiment.

[0017] FIG. 7 illustrates exemplary sub-images captured of an eye or artificial eye by a polarization-sensitive camera in accordance with an exemplary embodiment.

[0018] FIG. 8 illustrates resultant images and determinations from a polarization-sensitive camera in accordance with an exemplary embodiment.

[0019] FIG. 9 illustrates an exemplary method associated with an eye-tracking system including a polarization sensitive camera in accordance with an exemplary embodiment.

[0020] The figures depict various embodiments for purposes of illustration only. One skilled in the art will readily recognize from the following discussion that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles described herein.

DETAILED DESCRIPTION

[0021] Some embodiments of the present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, various embodiments of the invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Like reference numerals refer to like elements throughout.

[0022] As defined herein a "computer-readable storage medium," which refers to a non-transitory, physical or tangible storage medium (e.g., volatile or non-volatile memory device), may be differentiated from a "computer-readable transmission medium," which refers to an electromagnetic signal.

[0023] As referred to herein, structured polarization or polarization may refer to spatial and temporal properties of electric field vectors of an electromagnetic radiation that is utilized to illuminate an eye and surrounding tissues of the eye.

[0024] As referred to herein, a polarization-sensitive camera may refer to a single or multipixel array which may be utilized to sense or record a representation of a light field and may capture the polarization properties as well as intensity of a recorded signal associated with the representation of a light field.

[0025] As referred to herein, angle of polarization may refer to an angle of linearly polarized light (e.g., angle of linear polarization, angle of elliptical polarization) of a measured electric field vector and incidence plane.

[0026] As referred to herein, degree of polarization or degree of linear polarization may refer to a quantity used to describe the portion of an electromagnetic wave which is polarized. For example, a perfectly polarized wave may have a degree of polarization of 1, and an unpolarized wave may have a degree of polarization of 0.

[0027] As referred to herein, structured illumination profilometry may refer to structured illuminated light and/or active illumination profilometry mechanisms that may illuminate/emit an object (e.g., an eye(s)) with predetermined spatially variable intensity, variable polarization state(s) and/or variable wavelength(s) of light patterns and may capture/record these spatially variable intensity patterns as they are reflected by the object at an angle(s) in relation to a plane.

[0028] As referred to herein, a Metaverse may denote an immersive virtual/augmented reality world in which AR devices may be utilized in a network in which there may, but need not, be one or more social connections among users in the network.

[0029] It is to be understood that the methods and systems described herein are not limited to specific methods, specific components, or to particular implementations. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting.

[0030] HMD's including one or more near-eye displays may often be used to present visual content to a user for use in artificial reality applications. One type of near-eye display may include an enclosure that houses components of the near-eye display or is configured to rest on the face of a user, such as for example a frame. The near-eye display may include a waveguide that may direct light from a projector to a location in front of a user's eyes. Because of human visual sensitivity, slight deviations in optical quality may be apparent to the user of a near-eye display. Additionally, tracking of the eyes of a user may be beneficial for graphics rendering or user peripheral input.

[0031] The present disclosure is generally directed to systems and methods for an improved eye tracking system based on user eye disparity information for artificial reality devices. Examples in the present disclosure may include head-mounted displays and other artificial reality devices that may include an enclosure with a polarization-sensitive camera coupled with the enclosure. A waveguide may be configured to direct images from a light projector or light source to one or more eyes of a user.

Exemplary System Architecture

[0032] FIG. 1 illustrates an example head-mounted display (HMD) 100 associated with artificial reality content. HMD 100 may include enclosure 102 (e.g., an eyeglass frame), a polarization-sensitive camera 104, a waveguide 108, and a light source 110. Waveguide 108 may be configured to direct images to a user's eye. In some examples, head-mounted display 100 may be implemented in the form of augmented-reality glasses or Metaverse reality devices. Accordingly, the waveguide 108 may be at least partially transparent to visible light to allow the user to view a real-world environment through the waveguide 108. FIG. 1 also shows a representation of an eye (e.g., eye 106) that may be a real eye or an artificial eye-like object that may be for testing or using HMD 100.

[0033] Tracking of eye 106 may be beneficial for graphics rendering or user peripheral input. In existing systems, it may be difficult to track depth of an eye (e.g., eye 106) and eye rotation due to the centrosymmetric nature of the eye. Also, in existing systems due to practical limitations of structured illumination imaging the direction of the eye gaze may be unable to be reliably captured with sufficient accuracy for full eye tracking with a desired resolution (e.g., a desired resolution of 0.01 degree). Some of the existing systems may require a camera to respond to the reflection off the eyes or sensors with low accuracy. The exemplary embodiments of the present disclosure may overcome these drawbacks of existing or conventional systems by providing increased accuracy in eye tracking based, in part, on utilizing the polarization-sensitive camera 104, as described more fully below.

[0034] The polarization-sensitive camera 104 and the light source 110 may be located on frame 102 in different positions. The polarization-sensitive camera 104 may be arranged or located along a width of a section of frame 102. In some other examples, the polarization-sensitive camera 104 may be arranged on one side of frame 102 (e.g., a side of frame 102 nearest to an eye of a user). Alternatively, in some examples, the polarization-sensitive camera 104 may be located on waveguide 108. The light source 110 may project or illuminate light having one or more known polarization states and having uniform intensity into waveguide 108.

Exemplary Communication Device

[0035] FIG. 2 illustrates a block diagram of an exemplary hardware or software architecture of a communication device such as, for example, user equipment (UE) 30. In some exemplary embodiments, the UE 30 may be a computer system such as for example HMD 100, smart glasses, an augmented or virtual reality device or Metaverse reality device, a desktop computer, notebook or laptop computer, netbook, a tablet computer (e.g., a smart tablet), e-book reader, GPS device, a camera (e.g. polarization-sensitive camera 104), personal digital assistant, handheld electronic device, cellular telephone, smartphone, smart watch, charging case, or any other suitable electronic device. As shown in FIG. 2, the UE 30 (also referred to herein as node 30) may include a processor 32, non-removable memory 44, removable memory 46, a speaker or microphone 38, a keypad 40, a display, touchpad, or indicators 42, a power source 48, a global positioning system (GPS) chipset 50, and other peripherals 52. The power source 48 may be capable of receiving electric power for supplying electric power to the UE 30. For example, the power source 48 may include an alternating current to direct current (AC-to-DC) converter allowing the power source 48 to be connected or plugged to an AC electrical receptable or Universal Serial Bus (USB) port for receiving electric power. The UE 30 may also include one or more cameras 54. In an exemplary embodiment, the camera(s) 54 may be a smart camera configured to sense images or video appearing within one or more bounding boxes. The UE 30 may also include communication circuitry, such as a transceiver 34 and a transmit or receive element 36. It will be appreciated the UE 30 may include any sub-combination of the foregoing elements while remaining consistent with an embodiment.

[0036] The processor 32 may be a special purpose processor, a digital signal processor (DSP), a plurality of microprocessors, one or more microprocessors in association with a DSP core, a controller, a microcontroller, Application Specific Integrated Circuits (ASICs), Field Programmable Gate Array (FPGAs) circuits, any other type of integrated circuit (IC), a state machine, and the like. In general, the processor 32 may execute computer-executable instructions stored in the memory (e.g., memory 44 or memory 46) of the node 30 in order to perform the various required functions of the node. For example, the processor 32 may perform signal coding, data processing, power control, input or output processing, or any other functionality that enables the node 30 to operate in a wireless or wired environment. The processor 32 may run application-layer programs (e.g., browsers) or radio access-layer (RAN) programs or other communications programs. The processor 32 may also perform security operations such as authentication, security key agreement, or cryptographic operations, such as at the access-layer and/or application layer for example.

[0037] The processor 32 is coupled to its communication circuitry (e.g., transceiver 34 and transmit/receive element 36). The processor 32, through the execution of computer executable instructions, may control the communication circuitry in order to cause the node 30 to communicate with other nodes via the network to which it is connected.

[0038] The transmit/receive element 36 may be configured to transmit signals to, or receive signals from, other nodes or networking equipment. For example, in an exemplary embodiment, the transmit/receive element 36 may be an antenna configured to transmit and/or receive radio frequency (RF) signals. The transmit/receive element 36 may support various networks and air interfaces, such as wireless local area network (WLAN), wireless personal area network (WPAN), cellular, and the like. In yet another exemplary embodiment, the transmit/receive element 36 may be configured to transmit and/or receive both RF and light signals. It will be appreciated that the transmit/receive element 36 may be configured to transmit and/or receive any combination of wireless or wired signals. The transmit/receive element 36 may also be configured to connect the UE 30 to an external communications network, such as network 12, to enable the UE 30 to communicate with other nodes (e.g., other UEs 30, network device 160, etc.) of the network.

[0039] The transceiver 34 may be configured to modulate the signals that are to be transmitted by the transmit/receive element 36 and to demodulate the signals that are received by the transmit/receive element 36. As noted above, the node 30 may have multi-mode capabilities. Thus, the transceiver 34 may include multiple transceivers for enabling the node 30 to communicate via multiple radio access technologies (RATs), such as universal terrestrial radio access (UTRA) and Institute of Electrical and Electronics Engineers (IEEE 802.11), for example.

[0040] The processor 32 may access information from, and store data in, any type of suitable memory, such as the non-removable memory 44 and/or the removable memory 46. For example, the processor 32 may store session context in its memory, as described above. The non-removable memory 44 may include RAM, ROM, a hard disk, or any other type of memory storage device. The removable memory 46 may include a subscriber identity module (SIM) card, a memory stick, a secure digital (SD) memory card, and the like. In other exemplary embodiments, the processor 32 may access information from, and store data in, memory that is not physically located on the node 30, such as on a server or a home computer.

[0041] The processor 32 may receive power from the power source 48, and may be configured to distribute and/or control the power to the other components in the node 30. The power source 48 may be any suitable device for powering the node 30. For example, the power source 48 may include one or more dry cell batteries (e.g., nickel-cadmium (NiCd), nickel-zinc (NiZn), nickel metal hydride (NiMH), lithium-ion (Li-ion), etc.), solar cells, fuel cells, and the like. The processor 32 may also be coupled to the GPS chipset 50, which may be configured to provide location information (e.g., longitude and latitude) regarding the current location of the node 30. It will be appreciated that the node 30 may acquire location information by way of any suitable location-determination method while remaining consistent with an exemplary embodiment.

[0042] FIG. 3 illustrates an exemplary zoomed view of HMD 100 that includes waveguide 108, frame 102, light source 110, and polarization-sensitive camera 104 in the dashed circle A of FIG. 1.

[0043] FIG. 4 illustrates an exemplary zoomed side view of FIG. 3. Polarization-sensitive camera 104 may obtain information from waveguide 108. In an example, polarization-sensitive camera 104 may detect changes in polarization states and polarization angles associated with light being reflected from a light source 110. In this regard, light projected to an eye (e.g., eye 106) may be reflected to the polarization-sensitive camera 104. In some examples, the polarization-sensitive camera 104 may be configured to include a quantity or number of pixels, such as, for example, four groups of pixels and may include polarizers (e.g., linear polarizers) in front of the polarization-sensitive camera. In this regard, in some examples, the polarizers may be integrated in front of an image sensor of the polarization-sensitive camera or may be fused/integrated with the image sensor. In some examples, a lens of the polarization-sensitive camera may be a final element after an image sensor and a polarizer array. Each pixel in the four groups of pixels may be recording complementary information from approximately the same area of an object (e.g., eye 106). The complementary information may be different polarization states of light filtered by polarizers at various angles (e.g., 0°, 45°, 90°, 135°). In an example, one group of the four groups of pixels may record light filtered by a polarizer(s) at a first angle (e.g., 0°). A second group of the four groups of pixels may record light filtered by a polarizer(s) at a second angle (e.g., 45°). A third group of the four groups of pixels may record light filtered by a polarizer(s) at a third angle (e.g., 90°). A fourth group of the four groups of pixels may record light filtered by a polarizer(s) at a fourth angle (e.g., 135°). The complementary information may then be utilized by a processing device (e.g., processor 32) to determine particular parameters of light (e.g., angle of polarization and/or degree of polarization) projected to the polarization-sensitive camera 104. The polarizers of the polarization-sensitive camera 104 may be rotated at various angles (e.g., 0°, 45°, 90°, 135°) during a same image capture (e.g., rotated (e.g., simultaneously) during a single image capture of an eye(s)). In some other examples, the polarization-sensitive camera 104 may include a quantity or number of pixels other than four groups of pixels. For example, in some other exemplary embodiments, two groups of pixels may be utilized for two orthogonally arranged polarizers or any larger number of polarizers or other types of polarization filters or polarization steering elements such as meta surfaces. In this regard, angles for the two orthogonally arranged polarizers may be 0° and 90° for example. In another example, three groups of pixels may be utilized for three polarizers. For the three polarizers, the angles may be 0°, 60° and 120°, for example. In this regard, the polarization-sensitive camera 104 may be configured to capture four groups of pixels or sub-images (e.g., sub-images 714 of FIG. 7) simultaneously (e.g., in a single image capture) based on an image capture. The captured four groups of pixels or sub-images 714 may be polarizers and may be oriented at 0°, 45°, 90°, and 135° based on the polarizers (e.g., linear polarizers) included in the polarization-sensitive camera 104.

[0044] In some examples, the polarization-sensitive camera 104 may be configured to sum or combine the four sub-images 714 to generate a reflectivity map as an indication of intensity information. The summed or combined image of the sub-images 714 may be a single full image (e.g., full image 716 of FIG. 7) in which each of the angles of the sub-images 714 may be summed by the polarization-sensitive camera 104. In an alternative example, a determination may be performed using the pixel values of the four sub-images 714 as inputs to determine Stokes parameters, a Mueller matrix or other derivative parameters such as, for example, angle of polarization and degree of polarization which may be utilized to sum or combine the four sub-images 714 to be a single full image (e.g., full image 716). The polarization-sensitive camera 104 may be configured such that one group of pixels (e.g., one group of four groups of pixels) may be optimized to capture to a certain polarization orientation which may cause changes in intensity of light associated with a captured image (e.g., an image of an eye(s)). This optimization of capturing a certain polarization orientation may block out other groups of pixels that may have a polarization state which may be different from an optimized parameter associated with the one group of pixels, thus causing changes in recorded intensity (e.g., light intensity). In some examples, the optimized parameter may be the angle of polarization filters (e.g., polarizers) that may be placed in front of camera pixels.

[0045] FIG. 5 illustrates an example of structured polarization according to an exemplary embodiment. In the example of FIG. 4, waveguide 108 may further comprise polarization grating 112 between two supporting gratings 109, 111. The light source 110 may, for example, illuminate unpolarized light with uniform intensity. In this regard, for example, the polarization grating 112 may be utilized to detect or sense the light emitted from light source 110 and may form an interferogram that has uniform intensity 119 and may have spatially structured polarization with a polarization angle 121 (e.g., in a range of 0 to 2π or 0° to 360°). An interferogram may be any recorded interference pattern, where the patterns may result from light interference. In the example of FIG. 4, the image associated with the polarization angle 121 may indicate the linear effect (e.g., the lines) of the polarization grating 112. In some examples, the polarization grating 112 may utilize the unpolarized light emitted from the light source 110 and may generate two light beams 115, 117 such that the two light beams may interfere with each other to form an illumination field and thereby create or generate the uniform intensity 119 associated with the two light beams 115, 117. In some examples, by utilizing the polarization grating 112, the unpolarized light detected by the polarization grating 112, which may be generated into light beams (e.g., light beams 115, 117) may have different polarization states or styles and may have different polarization angles (e.g., 0°, 45°, 90°, 135°). As such, the light beams generated by the polarization grating 112 may exhibit structured polarization (e.g., spatially spaced apart polarized light with different polarization angles) since the polarization grating 112 may be configured to be linearly movable or rotated at different angles while the unpolarized light from the light source 110 is being emitted. The polarization grating 112 may be moved by piezo-actuators or micro-electro-mechanical systems (MEMS). In example embodiments, the light beams 115, 117 may be generated by the polarization grating 112 using light emitted from a light source 110. In this regard, both of the light beams 115, 117 may be present/detected at once and does not require different instances/emissions of light emitted from light source 110. If combining the light beams 115, 117 with motion, this may require multiple images of an eye(s) to be captured with different patterns projected. The multiple images may then be used in a manner similar to phase shifting profilometry. The structured polarization light, generated by polarization grating 112, may be propagated or travel to an eye (106) of a user. The reflection of the structured polarized light may be captured by the polarized-sensitive camera 104, as described more fully below.

[0046] FIG. 6 illustrates the polarization-sensitive camera 104 may detect the reflected structured polarized light propagated from the grating 112 onto an eye (e.g., eye(s) 106) of a user. FIG. 7 illustrates exemplary sub-images 714 captured of an eye or artificial eye by a polarization-sensitive camera 104 according to an exemplary embodiment. As described above, the polarization-sensitive camera 104 may detect the reflected structured polarized light propagated from the polarization grating 112 onto an eye (e.g., eye(s) 106) of a user. In this example, the polarization-sensitive camera 104 may be configured to capture four sub-images 714 simultaneously in response to detecting the structured polarized light reflected from the eye (e.g., eye 106). As described above, the polarization-sensitive camera 104 may capture the four sub-images 714 based on, for example the four groups of pixels that the polarization-sensitive camera 104 has and based on the polarizers (e.g., linear polarizers) that the polarization-sensitive camera 104 has in a front portion of the polarization-sensitive camera 104. In some examples, the polarizers may be associated with a polarizer array, or alternatively the polarizers may be integrated within the polarizer array. The polarizers, associated with the four groups of pixels, may be comprised of four different angled polarizers (e.g., 0°, 90°, 45° and 135°) which may be placed on each pixel, where each block of four pixels may make up a determination unit. The relationship between the different angled or directional polarizers in a four-pixel block may allow for determination of both the degree and direction of polarization. With this configuration (or similar configuration), each of the four groups of pixels may have a different polarization filter, as described above. Collectively these four groups of pixels may sample different polarization states and the recorded signals may be used to define the surface angles and material properties such as a depolarization property of the object (e.g., an eye(s)) that is being imaged (e.g., captured as an image). It should be pointed out that four groups of pixels may be described herein as examples, for purposes of illustration and not of limitation. As such, in some alternative example embodiments, the groups of pixels may from two to more than four groups of pixels. For example, two groups of pixels may be configured for capturing two orthogonal states of polarization (e.g., angle of polarization 0°, angle of polarization 90°). As another example, three groups of pixels may have, or be associated with, micro-polarizer filters at other states of polarization (e.g., angle of polarization 0°, angle of polarization 135°, angle of polarization 90°).

[0047] The polarization-sensitive camera 104 may capture the four sub-images simultaneously in response to detecting an image (e.g., a same or single image) of the structured polarized light reflected from the eye (e.g., eye 106). For instance, in response to detecting the structured polarized light reflected from the eye, each of the different polarizers associated with (e.g., in front of) the polarization-sensitive camera 104 may enable the polarization-sensitive camera 104 to generate the sub-images 714A, 714B, 714C and 714D in which each of the sub-images may have different polarization angles or phases based on the polarizers.

[0048] Based on the detected structured polarized light reflected from the eye, and the polarizers being rotated at angles such as, for example, rotated simultaneously in a single image capture of the eye at 0°, 45°, 90°, and 135°, the polarization-sensitive camera 104 may capture each of the sub-images 714 with an optimized polarization angle or phase at 0°, 45°, 90°, and 135°. Each of the sub-images 714 having an optimized polarization angle or phase at 0°, 45°, 90°, and 135 may be denoted by sub-images 714A, 714B, 714C, and 714D respectively. Although polarization angles at 0°, 45°, 90°, and 135° are described herein as examples, for purposes of illustration and not of limitation, other polarization angles may be utilized by the exemplary embodiments. In some examples, the polarization-sensitive camera 104 may generate full image 716 based on summing or totaling each of the sub-images 714A, 714B, 714C, and 714D. In some examples, the full image 716 may be a reflectivity map. The reflectivity map may indicate the reflectivity properties of an object (e.g., eye 106) that the polarization-sensitive camera 104 may have captured as light (e.g., light 110) that is reflected from the object (e.g., eye 106). The reflectivity map may also include information about ratio or specular and diffuse reflections of the object (e.g., eye 106) based on the light (e.g., light beams 115, 117) that is reflected. The polarization-sensitive camera 104 may sum each of the sub-images 714 such there are no polarization angles shown in the full image 716 and as such there may not be any associated lines (that are shown in sub-images 714A, 714B, 714C, and 714D) in the full image 716. In some other examples, the polarization-sensitive camera 104 may generate an intensity map or intensity comparison image 718 that may compare intensity of the sub-images 714A, 714B, 714C, and 714D at random points to indicate the manner in which recorded intensity may vary at different polarization angles or phases.

[0049] FIG. 8 illustrates resultant images and determinations from a polarization-sensitive camera 104. For instance, FIG. 8 may illustrate polarization sensitive eye imaging which may provide information beneficial for segmentation and for determination of surface normals. Segmentation is a process that allows for the identification of different parts of the eye such as, for example, the iris, sclera, eye lids, etc. The determination of parts of the eye via segmentation may facilitate/aid in determining, by a processing device (e.g., processor 32), gaze and pupil position of an eye for eye tracking. In the example of FIG. 8, the polarization-sensitive camera 104 may capture an image 802 of an eye based on the reflected light from the eye (e.g., eye 106) generated from uniform illumination of light, emitted from a light source (e.g., light source 110), that may be polarized by polarization grating 112. Based on the captured image 802, a processor (e.g., processor 32) of the polarization-sensitive camera 104 may analyze the captured image 802 and may determine a degree of linear polarization 804 associated with the image 802. Additionally, based on evaluating the same captured image 802, the processor 32 of the polarization-sensitive camera 104 may determine an angle of polarization 806 (e.g., 0°, 45°, 90° or 135°, etc.) associated with the image 802. For instance, the processor 32 of the polarization-sensitive camera 104 may determine the angle associated with the grating(s) (e.g., grating lines) shown in an image (e.g., image 802) as the determined angle of polarization of the image.

[0050] The degree of linear polarization (DOLP) may indicate how much linearly polarized light there is at any point of the eye region versus the total light presented to the eye (e.g., light that includes other polarization states). In reflected light, similar to as described in the foregoing paragraphs, the degree of linear polarization may change as a function of the surface angle with respect to the angle of incidence of light. Alternatively, the degree of linear polarization may be different for different material types. For example, the degree of linear polarization may vary from the eye lid, pupil, iris, sclera, etc., thus allowing for determination of different portions of the eye.

[0051] Additionally, based on evaluating the same instance of the captured image 802, the processor 32 of the polarization-sensitive camera 104 may determine depth information. The depth information may be associated with one or more colors (e.g., cross hatchings 1, 2, 3) associated with an image denoting an angle of polarization (e.g., image 806). The depth information may be the optical distance being measured or determined between the polarization-sensitive camera 104 and areas or points associated with an object (e.g., an eye (e.g., eye 106)). In some examples, the distance may be denoted in increments of 2π. In this regard, the colors may represent a numerical value(s) associated with the measured distance. In some examples, a color such as, for example, blue may denote a distance farthest away from the polarization-sensitive camera 104 and an associated area(s) or point(s) on the object (e.g., eye 106). A color such as, for example, yellow (e.g., cross hatching 1) may denote a distance that is closest between the polarization-sensitive camera 104 and an associated area(s) or point(s) on the object (e.g., eye 106). Additionally, a color such as for example, green (e.g., cross hatching 2) may denote a distance between polarization-sensitive camera 104 and an associated area(s) or point(s) that is between the distances associated with blue color depth (e.g., cross hatching 3) information and the yellow color (e.g., cross hatching 1) depth information. As described above, in some examples, the blue color, yellow color, or green color may be denoted by different cross hatchings (e.g., cross hatching 1, cross hatching 2, cross hatching 3) to convey the depth information described above. In some examples, the depth information may indicate depth of various features associated with, for example, an iris, pupil, sclera, eyelid, etc. of an eye (e.g., eye 106). In view of the above, the processor 32 of the polarization-sensitive camera 104 may be able to determine image intensity (e.g., a reflectivity map), a degree of linear polarization, an angle of linear polarization and depth information from a single instance of a same captured image of a reflection of light from an object such as, for example, an eye(s).

[0052] Each of the four sub-images 714A, 714B, 714C, 714D may be processed using a single frame profilometry approach (e.g., Fourier phase profilometry) to determine intensity images and degree of angle of polarization. Determination of degree of linear polarization may be determined by the processor of the polarization-sensitive camera 104 using the surface normal of a captured image of an eye. The surface normal may be the angle between the angle of incidence (e.g., an angle between eye 106 and light source 110) and the angle of detection (e.g., an angle of eye 106 and the polarization-sensitive camera 104). The surface normal may also be the vector that is perpendicular to a surface (e.g., a surface of an eye) at a measured point. A polarization state of the light reflected from the surface may depend on the surface normal of the object (e.g., an eye). The degree of linear polarization may determine the polarization and intensity of eye 106 due to reflection of light source 110 captured by the sub-images 714 from camera 104. The degree of linear polarization may provide information as to what portion of the eye is being reflected, whether it is the iris, pupil, cornea or some other area of the eye. For example, skin is depolarizing and different surfaces on the eye may have different polarization properties (e.g., iris, sclera, pupil, cornea, etc.) and may be identified by evaluating a depolarization degree. In some examples, intensity images such as, for example, reflectivity maps may provide signals about orientation and states of an eye and may provide signals useful for segmentation. For instance, reflectivity maps may provide information for determining torsional eye movement.

[0053] Depth information determined by a processing device (e.g., processor 32), for example, may provide information about gaze direction of an eye. In some examples, depth information may also provide information or signals regarding a pupil position in three-dimensions (3D). An angle(s) of polarization, for example, may provide information regarding surface normals and may be utilized, by a processing device (e.g., processor 32), for determining gaze direction of an eye. The degree of linear polarization may be utilized, by a processing device (e.g., processor 32), for determining segmentation of the eye (e.g., pupil or iris segmentation). For example, segmentation may allow identification of the iris because it has distinctly different depolarization properties when compared to the surrounding areas of the eye (e.g., eye 106) such as the sclera, eyelids and/or pupil. Segmentation may be useful for pupil tracking, by a sensor (e.g., polarization-sensitive camera 104), as the iris may be identified using information from both intensity and degree of linear polarization channels. A high degree of polarization may be maintained as light may be back-reflected from the iris, while skin and sclera may depolarize the light. After segmentation is performed, the iris may be selected and then a structured illumination profilometry approach may be used for determining, by a processing device, a three-dimensional point cloud representing an iris and a pupil. The structured illumination profilometry approach may be performed by a processing device (e.g., processor 32) based on one or more images, captured by the polarization-sensitive camera 104 for example, of an iris that was illuminated with structured light (for example with a fringe pattern(s)) being processed after segmentation by utilizing a phase shifting profilometry or a Fourier profilometry approach or some other suitable profilometry approach. In some examples, by processing only the iris, the structured illumination profilometry process may be sped up and may also help with reduction of phase-unwrapping errors.

[0054] In response to determining the 3D point cloud, a plane may be fitted to the 3D point cloud representing the iris and the pupil and one or more tip/tilt parameters of the plane may be determined for example by a processing device. The plane may be an x-y plane, which may be tilted in a z axis. In some instances, for eye tracking purposes, an iris may, initially, be determined to be flat. However, as the eye gaze changes, the eyeball may be rotating and as such tip and tilt parameters of the iris may be changing proportionally to the gaze direction. Since the eyeball may be rotating, the tip and tilt parameters may be associated with a 3D representation of an iris changing proportionally to the gaze direction of the eyeball. In this regard, for example, the x-y plane may be determinably fitted to the representation of the iris and the tip/tilt parameters may be extracted from the 3D point cloud to track the changes of the gaze of the eye, for eye tracking purposes. In some examples, the tip/tilt parameters may be extracted from the 3D point cloud by a processing device (e.g., processor 32). The tip and tilt parameters may denote an angle of the plane (e.g., x-y plane) in relation to a reference coordinate system associated with the plane. In other words, the tip and tilt parameters may quantify an average slope of the representation of the iris, associated with the 3D point cloud, in both the x and y directions associated with the plane. The tip and tilt parameters of a fitted surface (e.g., eye surface) in the plane is proportional to the gaze direction of an eye(s). Additionally, the change of an angle(s) of polarization at any point on the iris or sclera of an eye may be determined for eye tracking as the changes of both angle(s) of polarization and degree(s) of polarization is proportional to the change in the surface angle of a moving eye(s).

[0055] FIG. 9 illustrates an exemplary method associated with an eye-tracking system with a polarization-sensitive camera according to an exemplary embodiment. At step 900, a device (e.g., HMD 100) may direct light into a user's eye 106 via a waveguide 108 from a light source 110. At step 910, a device (e.g., HMD 100) may detect a change in a polarization state(s), a degree of linear polarization, or angle of polarization based on a captured image of an eye(s). The captured image of the eye(s) may be determined based on light reflected from the eye(s) of a user being detected and captured by a polarization-sensitive camera 104. The polarization-sensitive camera may respond to eye reflection data. A device such as, for example, HMD 100 may utilize this eye reflection data to determine eye polarization parameters (e.g., degree of polarization, angle or phase of polarization, etc.). At step 920, a device (e.g., HMD 100) may compare the change of the polarization state(s), the degree of linear polarization, or the angle of polarization to a predetermined threshold(s). At step 930, a device (e.g., HMD 100) may determine, based on the comparison, that an eye-tracking action occurred. At step 940, a device (e.g., HMD100) may send an indication (e.g., an alert) of detected eye movement (e.g., eye position change) that an eye-tracking action occurred (e.g., detection of eye movement by a certain amount). At step 950, a device (e.g., HMD 100) may update a display (e.g., display 42) based on the indication (e.g., an alert).

[0056] The method may be iterative and may continually compare light changes associated with movement of an eye(s).

Alternative Embodiments

[0057] The foregoing description of the embodiments has been presented for the purpose of illustration; it is not intended to be exhaustive or to limit the patent rights to the precise forms disclosed. Persons skilled in the relevant art may appreciate that many modifications and variations are possible in light of the above disclosure.

[0058] Some portions of this description describe the embodiments in terms of algorithms and symbolic representations of operations on information. These algorithmic descriptions and representations are commonly used by those skilled in the data processing arts to convey the substance of their work effectively to others skilled in the art. These operations, while described functionally, computationally, or logically, are understood to be implemented by computer programs or equivalent electrical circuits, microcode, or the like. Furthermore, it has also proven convenient at times, to refer to these arrangements of operations as modules, without loss of generality. The described operations and their associated modules may be embodied in software, firmware, hardware, or any combinations thereof.

[0059] Any of the steps, operations, or processes described herein may be performed or implemented with one or more hardware or software modules, alone or in combination with other devices. In one embodiment, a software module is implemented with a computer program product comprising a computer-readable medium containing computer program code, which may be executed by a computer processor for performing any or all of the steps, operations, or processes described.

[0060] Embodiments also may relate to an apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a computing device selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a non-transitory, tangible computer readable storage medium, or any type of media suitable for storing electronic instructions, which may be coupled to a computer system bus. Furthermore, any computing systems referred to in the specification may include a single processor or may be architectures employing multiple processor designs for increased computing capability.

[0061] Embodiments also may relate to a product that is produced by a computing process described herein. Such a product may comprise information resulting from a computing process, where the information is stored on a non-transitory, tangible computer readable storage medium and may include any embodiment of a computer program product or other data combination described herein.

[0062] The language used in the specification has been principally selected for readability and instructional purposes, and it may not have been selected to delineate or circumscribe the inventive subject matter. It is therefore intended that the scope of the patent rights be limited not by this detailed description, but rather by any claims that issue on an application based hereon. Accordingly, the disclosure of the embodiments is intended to be illustrative, but not limiting, of the scope of the patent rights, which is set forth in the following claims.

WHAT IS CLAIMED:

1. A head mounted device comprising:

a waveguide comprising a front surface and a rear surface, wherein the waveguide is configured to guide light onto an eye of a user to generate an image of the eye associated with a reflection of the light from the eye; and

a polarization-sensitive camera configured to detect one or more changes in polarization phase or intensity based on the image, and wherein the polarization-sensitive camera is configured to capture a plurality of sub-images associated with the image.

2. A method comprising:

detecting by a polarization camera a change in a polarization phase or intensity of light;

comparing the change of the polarization phase or the intensity of light to a predetermined threshold;

determining, based on the comparison, that an eye-tracking action occurred;

sending an indication that an eye-tracking action occurred; and

updating, based on the indication, a display.

ABSTRACT OF THE DISCLOSURE

Methods and systems for using a polarization-sensitive camera to track changes in eye movement of a user are provided. The system may include a light source for directing light into an eye(s) of a user via a waveguide(s). The light reflected from the eye(s) may be captured by a polarization-sensitive camera configured to detect eye polarization phase change(s). The polarization-sensitive camera may utilize the polarization phase change(s) information to determine one or more eye polarization parameters. The eye polarization parameters may be utilized by a head mounted device of the system to determine eye tracking features associated with orientation and states of the eye(s), gaze direction of the eye(s) or segmentation of the eye(s).

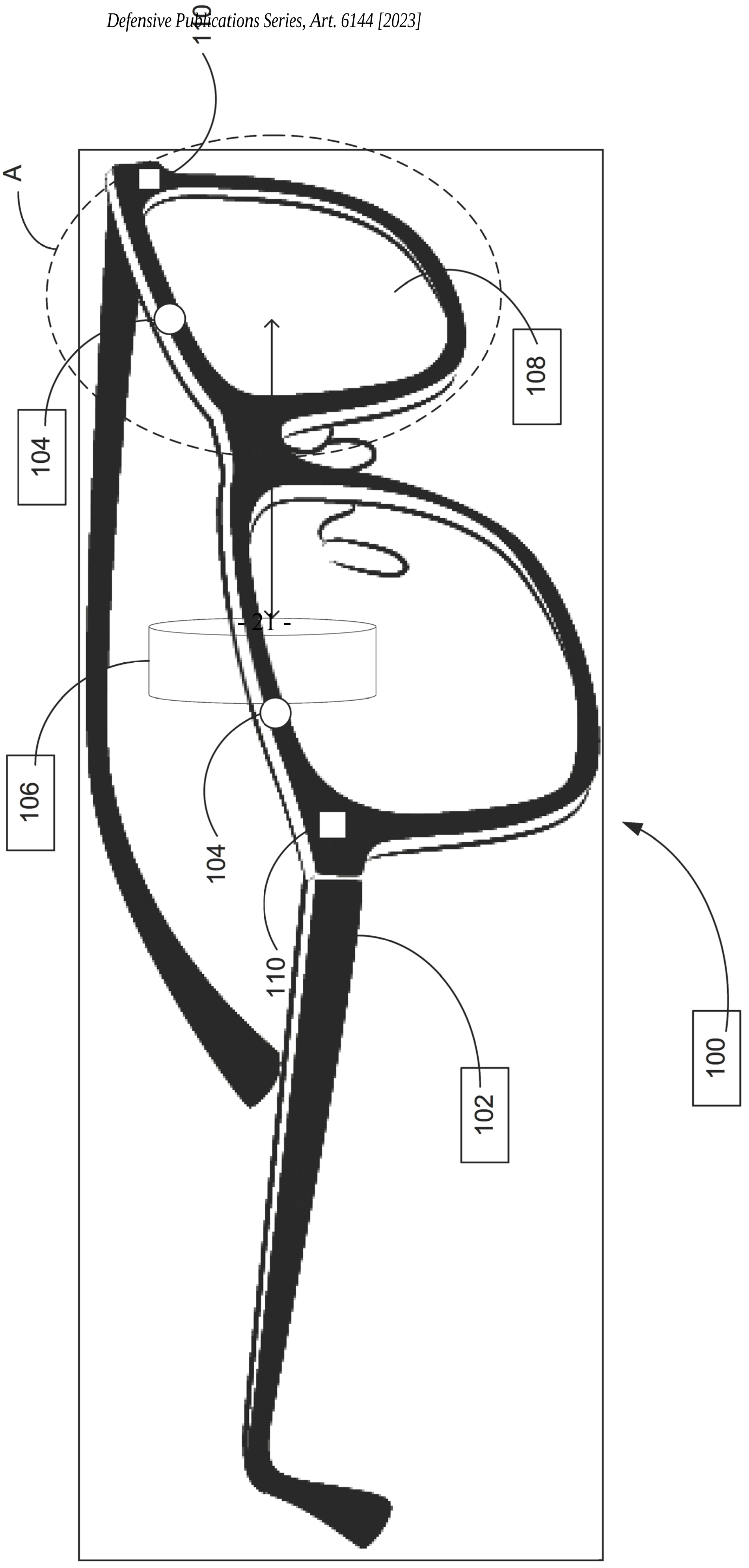

FIG. 1

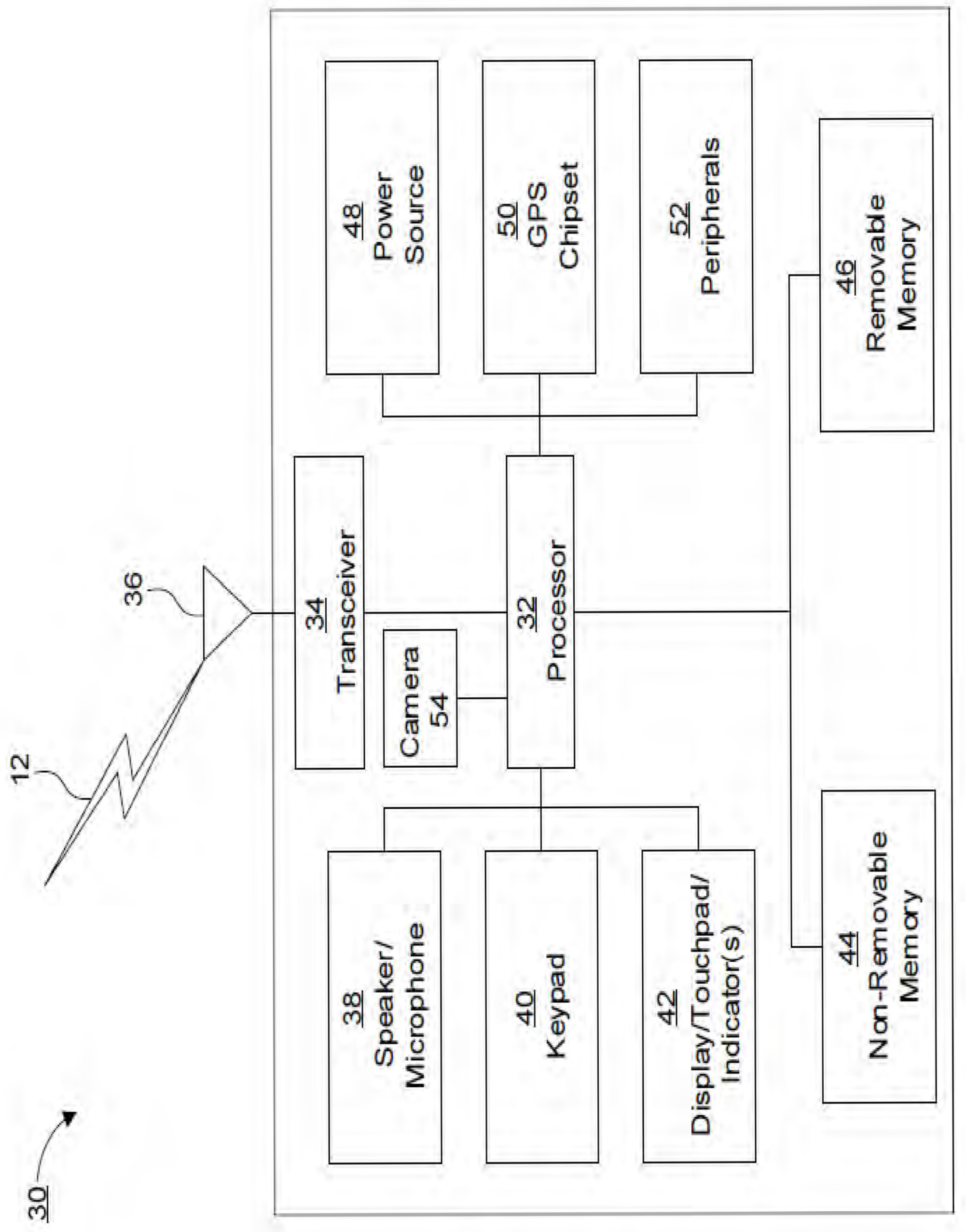
30
12
36
34
Transceiver
38
Speaker/
Microphone
40
Keypad
42
Display/Touchpad/
Indicator(s)
Camera
54
32
Processor
44
Non-Removable
Memory
46
Removable
Memory
48
Power
Source
50
GPS
Chipset
52
Peripherals

FIG. 2

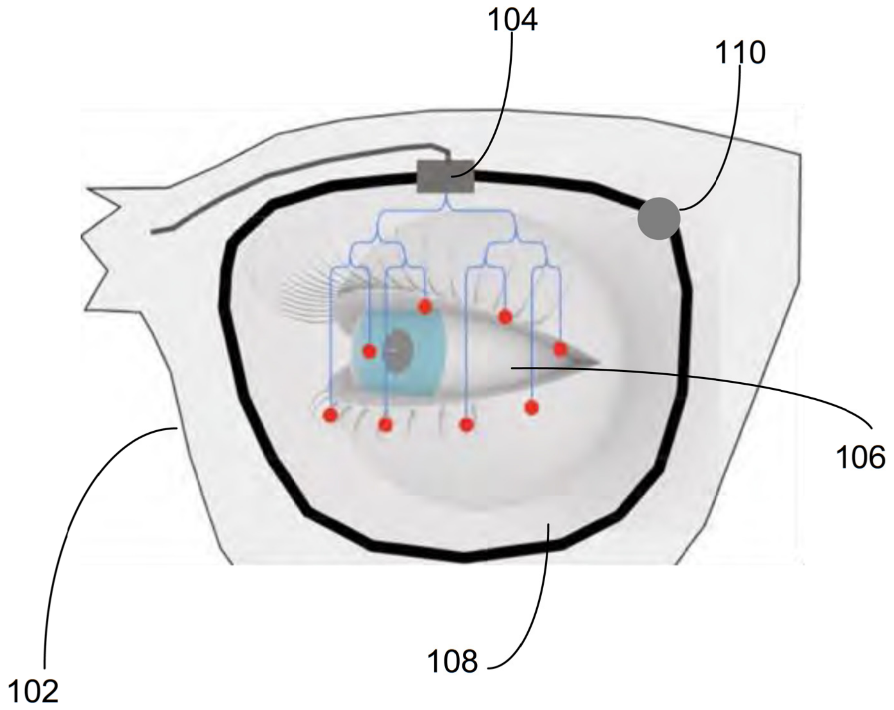

FIG. 3

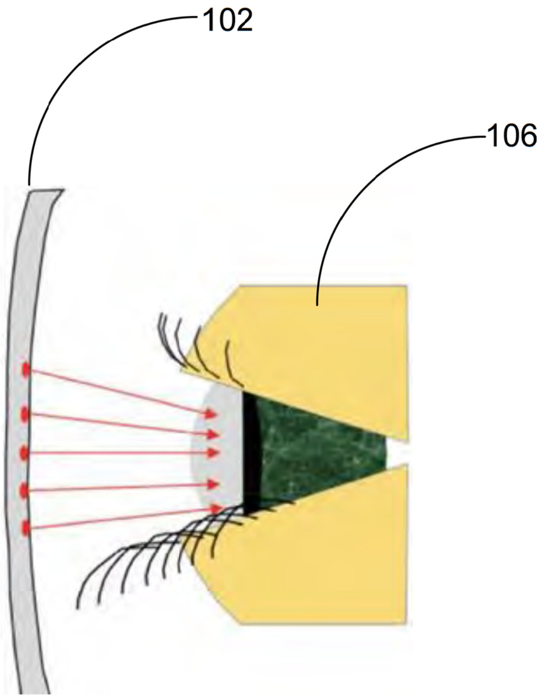

FIG. 4

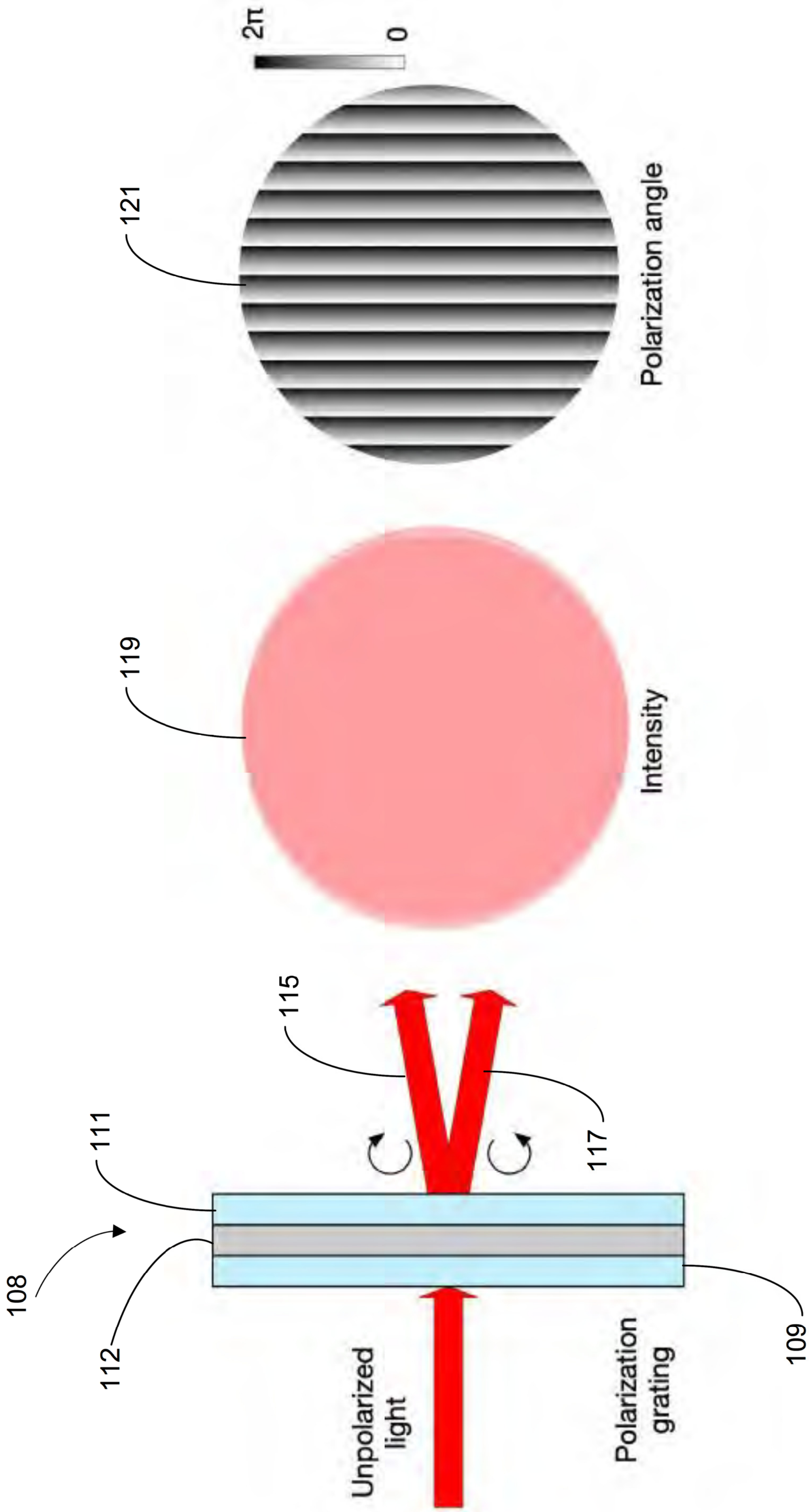
108
112
111
109
Unpolarized light
Polarization grating
115
117
119
Intensity
121
Polarization angle
2π
0

FIG. 5

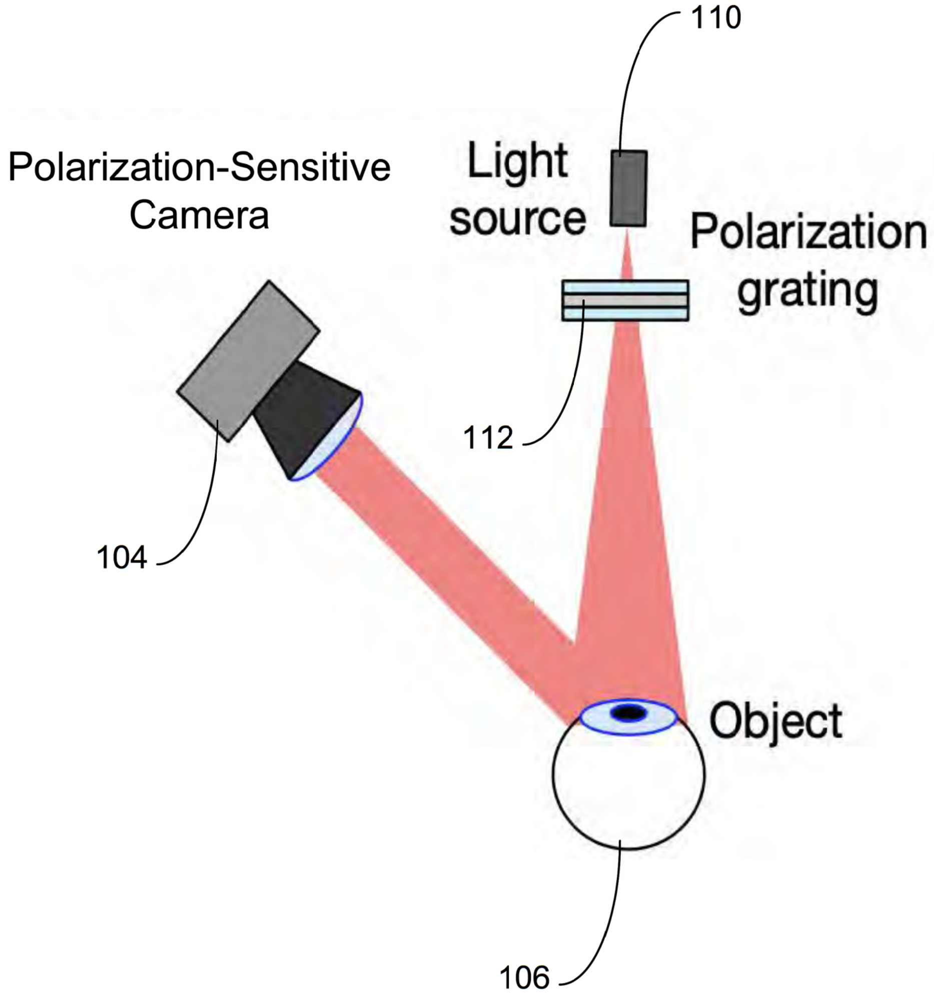
110
Polarization-Sensitive Camera
Light source
Polarization grating
112
104
Object
106

FIG. 6

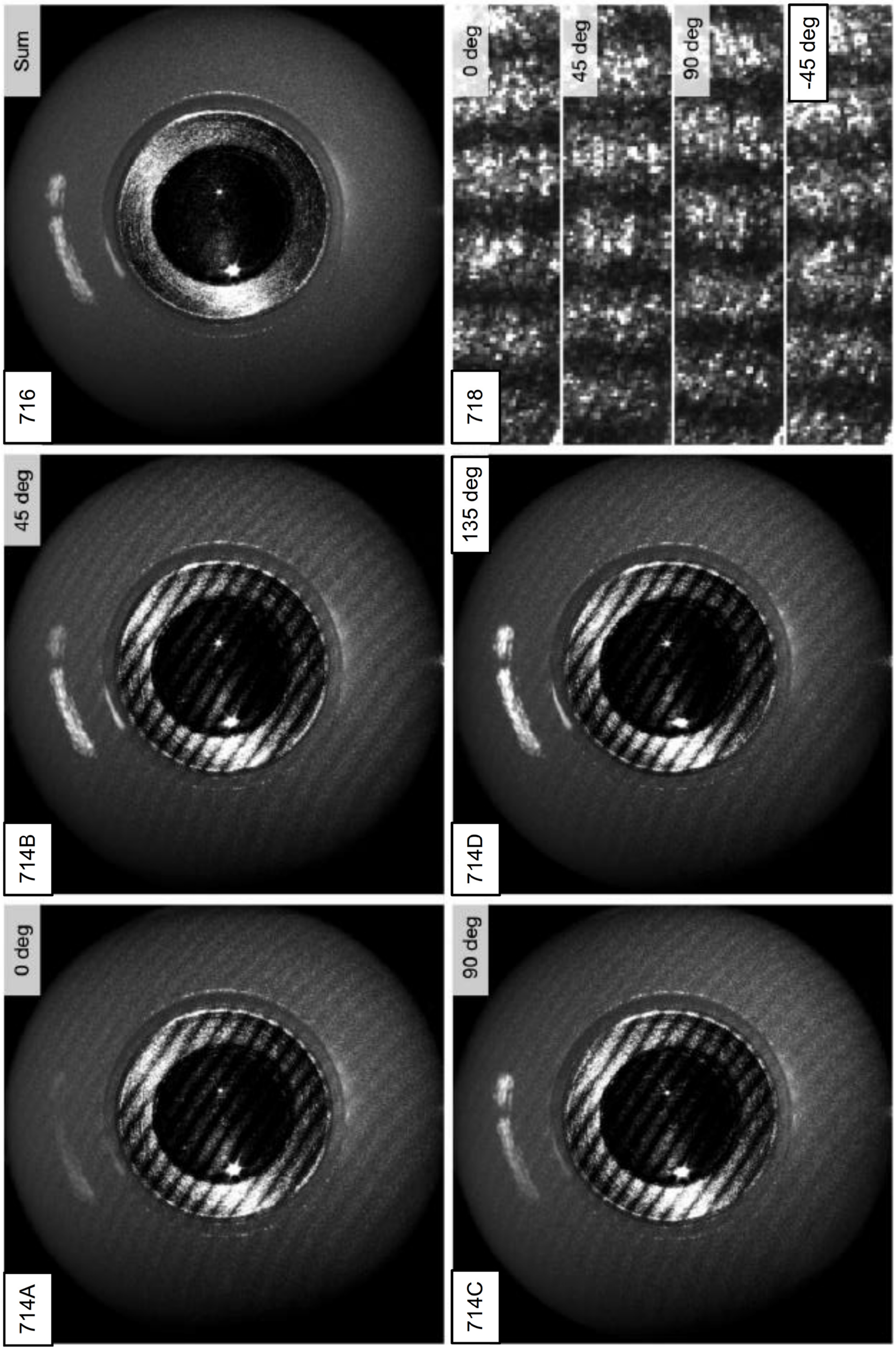
714A
0 deg
714B
45 deg
716
Sum
714C
90 deg
714D
135 deg
718
0 deg
45 deg
90 deg
-45 deg
714

FIG. 7

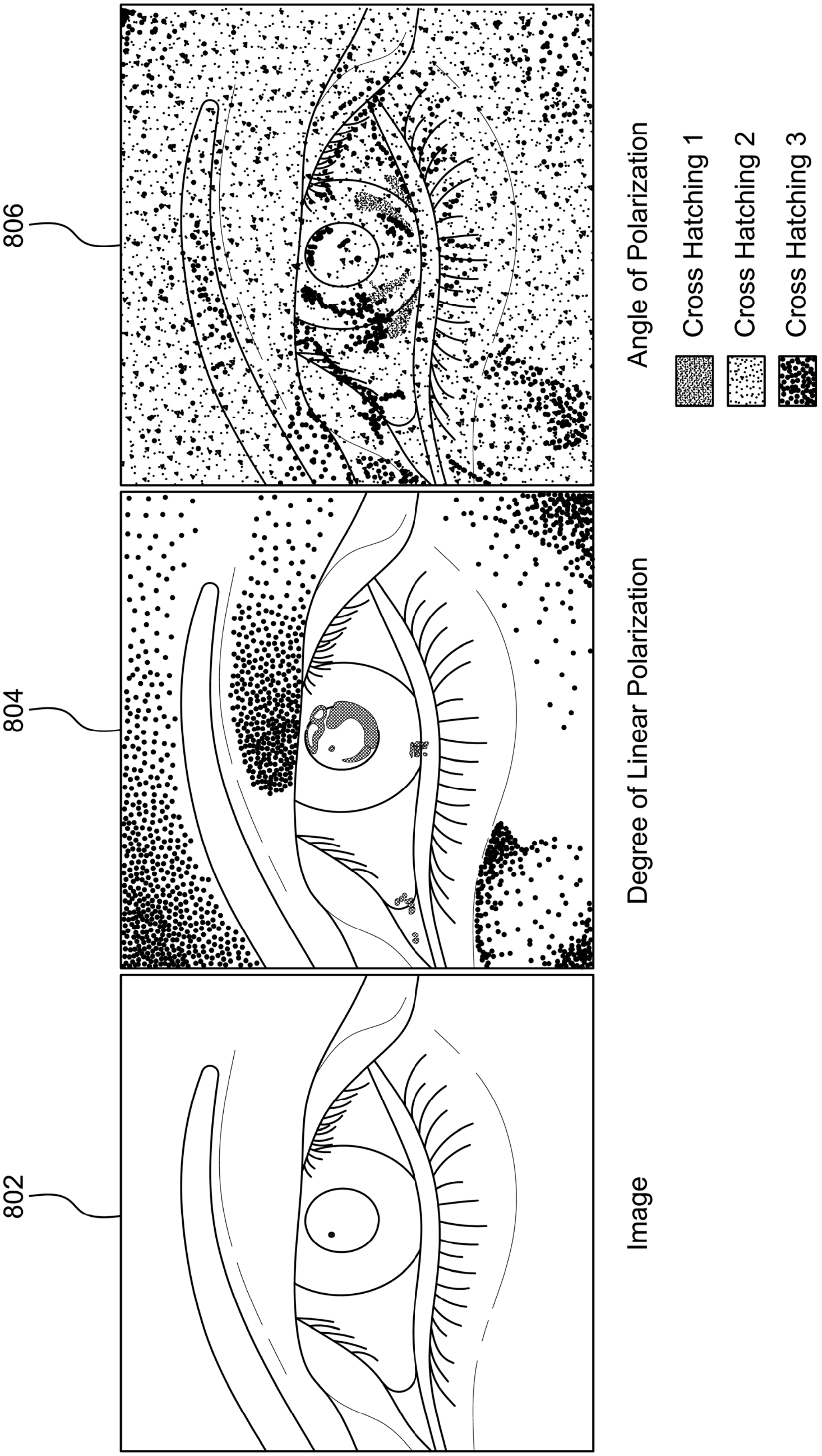
802
Image
804
Degree of Linear Polarization
806
Angle of Polarization
Cross Hatching 1
Cross Hatching 2
Cross Hatching 3

FIG. 8

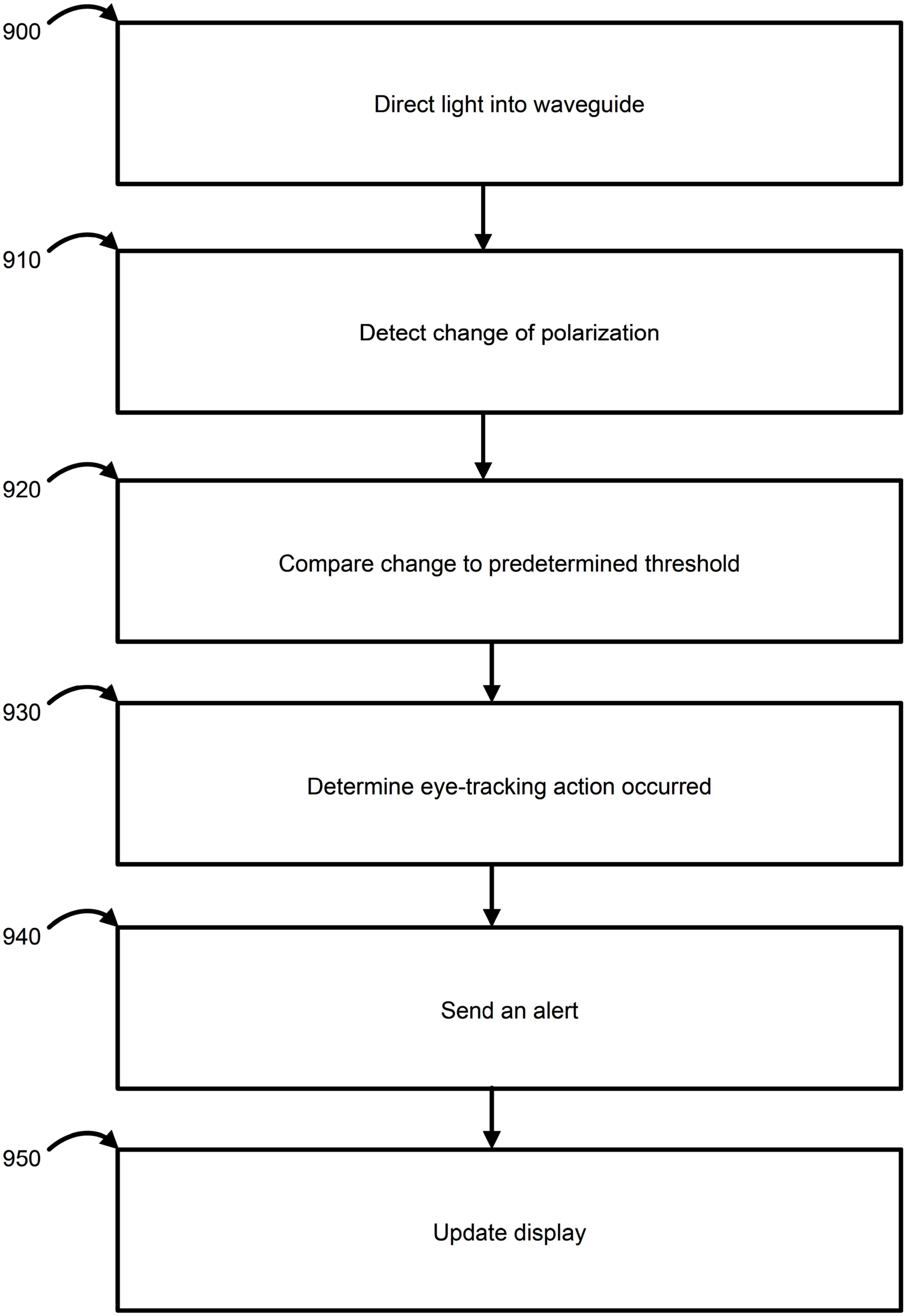
900
Direct light into waveguide
910
Detect change of polarization
920
Compare change to predetermined threshold
930
Determine eye-tracking action occurred
940
Send an alert
950
Update display

FIG. 9