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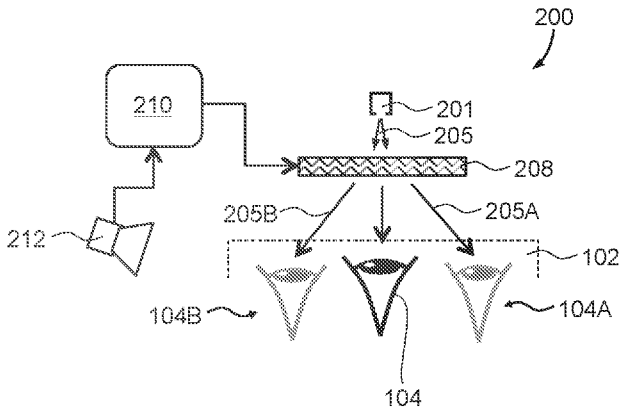


FIG. 2

(57) Abstract: A pupil-replicating lightguide includes a slab of transparent material, a switchable out-coupling grating for out-coupling portions of image light to propagate towards an eyebox, and a switchable tracking grating for redirecting tracking light carrying an eye image towards an eye tracking camera. One of the two gratings may be turned ON while the other is turned OFF, in a time-sequential manner, allowing the combined use of the pupil-replicating lightguide for carrying image light and eye tracking light.

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# EYE TRACKING WITH SWITCHABLE GRATINGS

## REFERENCE TO RELATED APPLICATION

**[0001]** This application claims priority from U.S. Provisional Patent Application No. 63/286,349 entitled "Active Gratings in Pupil-Replicated Displays and Illuminators", and U.S. Provisional Patent Application No. 63/286,230 entitled "Active Fluidic Optical Element", both filed on December 6, 2021.

## [0002] TECHNICAL FIELD

**[0003]** The present disclosure relates to tunable optical devices, and in particular to eye tracking systems usable in visual display systems, as well as components, modules, and methods for eye tracking and visual display systems.

## BACKGROUND

**[0004]** Visual displays provide information to viewer(s) including still images, video, data, etc. Visual displays have applications in diverse fields including entertainment, education, engineering, science, professional training, advertising, to name just a few examples. Some visual displays, such as TV sets, display images to several users, and some visual display systems, such s near-eye displays (NEDs), are intended for individual users.

**[0005]** An artificial reality system generally includes an NED (e.g., a headset or a pair of glasses) configured to present content to a user. The near-eye display may display virtual objects or combine images of real objects with virtual objects, as in virtual reality (VR), augmented reality (AR), or mixed reality (MR) applications. For example, in an AR system, a user may view images of virtual objects (e.g., computer-generated images (CGIs)) superimposed with the surrounding environment by seeing through a "combiner" component. The combiner component including its light routing optics may be transparent to external light.

**[0006]** An NED is usually worn on the head of a user. Consequently, a large, bulky, unbalanced, and heavy display device with a heavy battery would be cumbersome and uncomfortable for the user to wear. Head-mounted display devices can benefit from a compact and efficient configuration, including efficient light sources and illuminators providing illumination of a display panel, high-throughput combiner components and ocular lenses, and other optical elements in the image forming train that can provide an image to a user's eye with minimal image distortions and artifacts.

## SUMMARY

**[0007]** According to a first aspect of the present invention, there is provided a near-

eye display comprising: an image projector for providing image light carrying an image in angular domain to an eye at an eyebox of the near-eye display; an eye tracking camera for receiving tracking light carrying an image of the eye at the eyebox; and a lightguide coupled to the image projector and the eye tracking camera, the lightguide comprising: a slab of transparent material for propagating the image light and the tracking light therein; a switchable out-coupling grating for out-coupling portions of the image light to propagate towards the eyebox; and a switchable tracking grating for redirecting the tracking light towards the eye tracking camera.

**[0008]** Optionally, the slab is configured to transmit external light to the eyebox, providing a field of view of outside environment to the eye; and both the switchable out-coupling grating and the switchable tracking grating are at least partially disposed in the field of view.

**[0009]** Optionally, the switchable out-coupling grating is switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating is above a first threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating below a second threshold; and the switchable tracking grating is switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating is above a third threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable tracking grating is below a fourth threshold.

**[0010]** Optionally, the first threshold is at least 10 times higher than the second threshold, and the third threshold is at least 10 times higher than the fourth threshold.

**[0011]** Optionally, the near-eye display further comprises a controller operably coupled to the switchable out-coupling grating and the switchable tracking grating and configured to: switch the switchable out-coupling grating to the high-efficiency state and switch the switchable tracking grating to the low-efficiency state during a first time interval; and switch the switchable out-coupling grating to the low-efficiency state and switch the switchable tracking grating to the high-efficiency state during a second, subsequent time interval.

**[0012]** Optionally, the controller is operably coupled to the image projector and is configured to cause the image projector to display the image in angular domain during the first time interval.

**[0013]** Optionally, the controller is operably coupled to the eye tracking camera and is configured to cause the eye tracking camera to obtain the image of the eye during the

second time interval.

**[0014]** Optionally, the lightguide is a pupil-replicating lightguide for propagating the image light and the tracking light by a series of internal reflections in the slab, wherein the tracking light is in-coupled into the slab by the switchable tracking grating, the pupil-replicating lightguide further comprising: an in-coupling grating for in-coupling the image light provided by the image projector into the slab; and an out-coupling tracking grating for out-coupling at least a portion of the tracking light from the slab and towards the eye tracking camera.

**[0015]** Optionally, the in-coupling grating is switchable, and wherein the out-coupling tracking grating is switchable.

**[0016]** Optionally, at least one of the switchable out-coupling grating or the switchable tracking grating comprises a switchable polarization volume hologram (PVH) grating.

**[0017]** Optionally, at least one of the switchable out-coupling grating or the switchable tracking grating comprises a switchable Pancharatnam–Berry phase (PBP) liquid crystal (LC) grating.

**[0018]** Optionally, at least one of the switchable out-coupling grating or the switchable tracking grating comprises a switchable liquid crystal (LC) surface relief grating.

**[0019]** Optionally, at least one of the switchable out-coupling grating or the switchable tracking grating comprises a fluidic grating.

**[0020]** According to a further aspect of the present invention, there is provided a method for displaying an image to an eye and tracking the eye, the method comprising: providing image light carrying an image in angular domain; propagating the image light in a slab of transparent material; during a first time interval, switching an out-coupling grating to a high-efficiency state to out-couple portions of the image light towards an eyebox; andduring a second, subsequent time interval, switching a tracking grating to a high-efficiency state to redirect tracking light carrying an image of the eye towards an eye tracking camera.

**[0021]** Optionally, the method further comprises using an image projector to display the image in angular domain during the first time interval.

**[0022]** Optionally, the method further comprises switching the out-coupling grating to a low-efficiency state during the second time interval, and switching the tracking grating to a low-efficiency state during the first time interval.

**[0023]** Optionally, an out-coupling efficiency of the out-coupling grating is at least ten times higher in the high efficiency state than in the low-efficiency state, and wherein an out-coupling efficiency of the tracking grating is at least ten times higher in the high efficiency state than in the low-efficiency state.

**[0024]** According to a further aspect of the present invention there is provided a pupil-replicating lightguide comprising: a slab of transparent material for propagating image light and tracking light, wherein in operation, the image light carries an image in angular domain to a user's eye at an eyebox, and the tracking light carries an image of the eye to an eye tracking camera; a switchable out-coupling grating for out-coupling portions of the image light to propagate towards the eyebox; and a switchable tracking grating for redirecting the tracking light towards the eye tracking camera.

**[0025]** Optionally, projections of the switchable out-coupling grating and the switchable tracking grating onto a clear aperture of the pupil-replicating lightguide overlap one another.

**[0026]** Optionally, at least one of the switchable out-coupling grating or the switchable tracking grating comprises at least one of: a switchable polarization volume hologram (PVH) grating; a switchable Pancharatnam–Berry phase (PBP) liquid crystal (LC) grating; a switchable liquid crystal (LC) surface relief grating; or a fluidic grating.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0027]** Exemplary embodiments will now be described in conjunction with the drawings, in which:

**[0028]** FIG. 1 is a schematic view of an eye illuminator for an eye tracking system, the illuminator including a plurality of illuminating light sources;

**[0029]** FIG. 2 is a schematic view of an eye tracking system including an illuminating light source coupled to a switchable grating configured to deviate the illuminating light towards an eye location at an eyebox;

**[0030]** FIG. 3 is a schematic view of a display apparatus using the eye illuminator of FIG. 2;

**[0031]** FIG. 4 is a flow chart of a method for tracking an eye at the eyebox;

**[0032]** FIG. 5 is a side cross-sectional view of a near-eye display with switchable out-coupling and tracking gratings;

**[0033]** FIG. 6 is a sequence diagram illustrating the operation of the display device of FIG. 5;

**[0034]** FIG. 7 is a flow chart of a method for displaying an image to an eye and

tracking the eye;

**[0035]** FIG. 8 shows side cross-sectional views of a tunable liquid crystal (LC) surface-relief grating of this disclosure;

**[0036]** FIG. 9A is a frontal view of an active Pancharatnam–Berry phase (PBP) liquid crystal (LC) grating usable in an eye tracker of this disclosure;

**[0037]** FIG. 9B is a magnified schematic view of LC molecules in an LC layer of the active PBP LC grating of FIG. 9A;

**[0038]** FIGs. 10A and 10B are side schematic views of the active PBP LC grating of FIGs. 9A and 9B, showing light propagation in OFF (FIG. 10A) and ON (FIG. 10B) states of the active PBP LC grating;

**[0039]** FIGs. 11A is a side cross-sectional view of a switchable polarization volume grating (PVH) usable in an eye tracker of this disclosure;

**[0040]** FIG. 11B is a diagram illustrating optical performance of the PVH of FIG. 11A;

**[0041]** FIG. 12A is a side cross-sectional view of a fluidic grating usable in an eye tracker of this disclosure, in an OFF state;

**[0042]** FIG. 12B is a side cross-sectional view of the fluidic grating of FIG. 12A in an ON state;

**[0043]** FIG. 13A is a side cross-sectional view of a lightguide including an acoustic actuator for creating a volume acoustic wave in the lightguide;

**[0044]** FIG. 13B is a side cross-sectional view of a lightguide including an acoustic actuator for creating a surface acoustic wave in the lightguide;

**[0045]** FIG. 14 is a view of an augmented reality (AR) display having a form factor of a pair of eyeglasses; and

**[0046]** FIG. 15 is a three-dimensional view of a head-mounted display (HMD) of this disclosure.

## DETAILED DESCRIPTION

**[0047]** While the present teachings are described in conjunction with various embodiments and examples, it is not intended that the present teachings be limited to such embodiments. On the contrary, the present teachings encompass various alternatives and equivalents, as will be appreciated by those of skill in the art. All statements herein reciting principles, aspects, and embodiments of this disclosure, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include

both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

**[0048]** As used herein, the terms "first", "second", and so forth are not intended to imply sequential ordering, but rather are intended to distinguish one element from another, unless explicitly stated. Similarly, sequential ordering of method steps does not imply a sequential order of their execution, unless explicitly stated. Throughout the specification, the terms “switchable” and “tunable” are used interchangeably.

**[0049]** Near-eye displays use eye trackers to determine viewer’s eyes position and orientation. This information is used to adjust the optical system’s accommodation distance to account for the eye pupil position, to redirect light towards the pupil for better optical throughput, to adjust the displayed content, etc.

**[0050]** An eye tracking system may include illuminators for illuminating the eye with invisible e.g. infrared light, and an eye tracking camera for obtaining a series of images of the eye illuminated by the illuminators. The illuminators may be disposed all around an eyebox defined as a geometrical area where the user’s eye may be located, to provide adequate illumination. The eye tracking illuminators, cameras, and the accompanying redirecting/focusing optics, as well as the display image forming optics need to be arranged in a tight space in front of and around the eye. This may represent a significant technical challenge.

**[0051]** In accordance with this disclosure, switchable grating structures may be used to provide a functional integration of the eye tracking optics into a near-eye display for better compactness, performance, and energy efficiency. In some embodiments, a switchable grating structure may be optically coupled to the light source for receiving and redirecting the illuminating light to a location of the eye at an eyebox, thus greatly reducing the required number of the illuminating light sources. In some embodiments, a switchable grating may be placed in an image forming optical path of an eye tracking system. Time division multiplexing may be used to switch the near-eye display between an image displaying mode and an eye tracking mode. For instance, the eye tracking may be performed in between visual frames provided to the user of the display, enabling a compact and efficient overall display configuration.

**[0052]** In accordance with the present disclosure, there is provided a near-eye display comprising an image projector for providing image light carrying an image in angular domain to an eye at an eyebox of the near-eye display, an eye tracking camera for receiving tracking light carrying an image of the eye at the eyebox, and a lightguide

coupled to the image projector and the eye tracking camera. The lightguide includes a slab of transparent material for propagating the image light and the tracking light in the slab, a switchable out-coupling grating for out-coupling portions of the image light to propagate towards the eyebox, and a switchable tracking grating for redirecting the tracking light towards the eye tracking camera. In embodiments where the slab is configured to transmit external light to the eyebox thereby providing a field of view of outside environment to the eye, both the switchable out-coupling grating and the switchable tracking grating may be at least partially disposed in the field of view.

**[0053]** The switchable out-coupling grating may be switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating is above a first threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating below a second threshold. Similarly, the switchable tracking grating may be switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating is above a third threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable tracking grating is below a fourth threshold. The first threshold may be e.g. at least 10 times or at least 100 times higher than the second threshold, and the third threshold may be e.g. at least 10 times or at least 100 times higher than the fourth threshold.

**[0054]** In some embodiments, the near-eye display may further include a controller operably coupled to the switchable out-coupling grating and the switchable tracking grating. The controller may be configured to switch the switchable out-coupling grating to the high-efficiency state and switch the switchable tracking grating to the low-efficiency state during a first time interval, and switch the switchable out-coupling grating to the low-efficiency state and switch the switchable tracking grating to the high-efficiency state during a second, subsequent time interval. The controller may be operably coupled to the image projector and configured to cause the image projector to display the image in angular domain during the first time interval.

**[0055]** In some embodiments, the lightguide is a pupil-replicating lightguide that propagates the image light and the tracking light by a series of internal reflections in the slab. The tracking light may be in-coupled into the slab by the switchable tracking grating. The pupil-replicating lightguide may further include an in-coupling grating for in-coupling the image light provided by the image projector into the slab, and an out-coupling tracking grating for out-coupling at least a portion of the tracking light from

the slab and towards the eye tracking camera. The in-coupling and/or out-coupling grating(s) may be switchable. At least one of the switchable out-coupling grating or the switchable tracking grating may include at least one of: a switchable polarization volume hologram (PVH) grating; a switchable Pancharatnam–Berry phase (PBP) liquid crystal (LC) grating; a switchable liquid crystal (LC) surface relief grating; or a fluidic grating, for example.

**[0056]** In accordance with the present disclosure, there is provided a method for displaying an image to an eye and tracking the eye. The method includes: providing image light carrying an image in angular domain; propagating the image light in a slab of transparent material; during a first time interval, switching an out-coupling grating to a high-efficiency state to out-couple portions of the image light towards an eyebox; and during a second, subsequent time interval, switching a tracking grating to a high-efficiency state to redirect tracking light carrying an image of the eye towards an eye tracking camera. The method may further include using an image projector to display the image in angular domain during the first time interval, switching the out-coupling grating to a low-efficiency state during the second time interval, and/or switching the tracking grating to a low-efficiency state during the first time interval. An out-coupling efficiency of the out-coupling grating may be e.g. at least ten times higher in the high efficiency state than in the low-efficiency state, and an out-coupling efficiency of the tracking grating may be e.g. at least ten times higher in the high efficiency state than in the low-efficiency state.

**[0057]** In accordance with the present disclosure, there is further provided a pupil-replicating lightguide comprising a slab of transparent material for propagating image light and tracking light, where in operation, the image light carries an image in angular domain to a user's eye at an eyebox, and the tracking light carries an image of the eye to an eye tracking camera. A switchable out-coupling grating out-couples portions of the image light to propagate towards the eyebox. A switchable tracking grating redirects the tracking light towards the eye tracking camera. Projections of the switchable out-coupling grating and the switchable tracking grating onto a clear aperture of the pupil-replicating lightguide may overlap one another. At least one of the switchable out-coupling grating or the switchable tracking grating may include at least one of: a switchable polarization volume hologram (PVH) grating; a switchable Pancharatnam–Berry phase (PBP) liquid crystal (LC) grating; a switchable liquid crystal (LC) surface relief grating; or a fluidic grating.

**[0058]** Illustrative embodiments having switchable gratings in the eye tracker's eye illumination path will now be considered. Referring to FIG. 1, an eyebox illuminator 100 includes a plurality of light sources 101 illuminating an eyebox 102. The light sources 101 may be e.g. semiconductor light sources such as light-emitting diodes (LEDs) or vertical cavity surface-emitting lasers (VCSELs) emitting illuminating light 105 preferably at a wavelength invisible to an eye 104, for example at a near-infrared wavelength of between 720nm and 1100nm, to avoid dazzling or distracting the viewer. The light sources 101 are spread over the entire eyebox 102 to provide illumination of the eye 104 at all possible locations of the eye 104 in the eyebox 102, including e.g. a first location 104A and a second location 104B. Only three such sources are shown for brevity.

**[0059]** The illumination of the eye 104 with a light source 101 may cause a specular reflection or glint 106 of the illuminating light 105 in an image of the eye 104 taken with an eye tracking camera. The location of the glint 106 in an image of the eye 104 relative to the eye pupil may facilitate the determination of orientation, i.e. the direction of gaze, of the eye 104. More than one glint 106 may be relied upon for eye orientation determination, and accordingly more than one light source 101 and/or a multi-emitter light source 101 may need to be provided at each location at the eyebox 102. The overall number of the light sources 101 required to illuminate the entire eyebox 102 may become quite large. This increases costs, complexity, and energy consumption of the eyebox illuminator 100.

**[0060]** Turning to FIG. 2, an eye tracking system 200 includes a light source 201 providing illuminating light 205 such as, for example, an LED, a VCSEL, a multi-emitter semiconductor light source, or another semiconductor light source. The light source 201 may operate in an invisible part of optical spectrum such as near-infrared light in a wavelength range between 720nm and 1100nm. A switchable grating structure 208 is optically coupled to the light source 201 for receiving and redirecting the illuminating light 205 to a location of the eye 104 at the eyebox 102. Examples of the switchable grating structure 208 will be provided further below. An eye tracking camera 212 is configured to obtain images of the eye 104 at the eyebox 102.

**[0061]** A controller 210 may be operably coupled to the switchable grating structure 208 and the eye tracking camera 212. The controller 210 may be suitably configured, for example programmed with software, firmware, and/or hard-wired, to determine the location of the eye 104 at the eyebox 102 from an image or a series of images obtained

by the eye tracking camera 212. The controller 210 may be configured to cause the switchable grating structure 208 to redirect the illuminating light 205 to the location of the eye 104 at the eyebox 102. For example, when the controller 210 analyzes images obtained by the eye tracking camera 212 and determines that the eye 104 is at the first location 104A, the controller 210 may cause the switchable grating structure 208 to redirect the illuminating light 205 in a first direction 205A towards the first location 104A. When the controller 210 determines that the eye 104 is at the second location 104B, the controller 210 may cause the switchable grating structure 208 to redirect the illuminating light 205 in a second direction 205B towards the second location 104B.

**[0062]** The eye tracking system 200 may be used in a near-eye display to determine at least one if a position or orientation of a user's eye at the eyebox of the display. Referring for a non-limiting illustrative example to FIG. 3, a near-eye display 300 includes a projector 352 for providing image light 321 carrying an image in angular domain for viewing by the eye 104 at the eyebox 102. Herein, the term "image in angular domain" means an image where different elements of the image (i.e. pixels of the image) are represented by angles of corresponding rays of the converging image light beam 115, the rays carrying optical power levels and/or color composition corresponding to brightness and/or color values of the image pixels. In the implementation shown, the projector 352 includes a microdisplay panel 354 coupled to a collimator 356, e.g. a lens, for converting an image in linear domain displayed by the microdisplay panel into the image in angular domain. A scanning projector may be used in place of the microdisplay-based projector 352. A scanning projector may scan or raster an image in angular domain pixel by pixel, or in groups of pixels.

**[0063]** The near-eye display 300 may further include a pupil-replicating lightguide 308, which carries the image light 321 generated by the microdisplay 354 to the eyebox 102 by propagating the image light 321 inside the pupil-replicating lightguide 308 by a series of internal reflections, delivering laterally offset portions 321A of the image light 321 to the eyebox 102. The image in angular domain may be directly viewed by the eye 104. The pupil-replicating lightguide 308 may include a grating in-coupler 314 and a grating out-coupler 316. The grating in-coupler 314 in-couples the image light 321 into the pupil-replicating lightguide 308, and the grating out-coupler out-couples the portions 321A of the image light 321 from the pupil-replicating lightguide 308.

**[0064]** The near-eye display 300 includes the eye tracking system 200 of FIG. 2. The light source 201 of the eye tracking system 200 provides the illuminating light 205

for illumination of the eye 104 at the eyebox 102 through the pupil-replicating lightguide 308, which is substantially transparent to the illuminating light 205. The switchable grating structure 208 is optically coupled to the light source 201 for receiving and redirecting the illuminating light 205 to a location of the eye 104 at the eyebox 102.

**[0065]** The location of the eye 104 at the eyebox 102 may be determined by the eye tracking camera 212 coupled to a controller 310, which is analogous to the controller 210 of the eye tracking system 200 of FIG. 2, further providing other functions related to operation of the near-eye display 300. The controller 310 may determine the location of the eye 104 at the eyebox 102 from an image obtained by the eye tracking camera 212, and cause the switchable grating structure 208 to redirect the illuminating light 205 to the location of the eye 104 at the eyebox 102, e.g. to the first location 104A or the second location 104B. The controller 310 may be further configured to determine the orientation of the eye 104 at the eyebox 102 by detecting a glint 206 of the illuminating light 205 in an image obtained by the eye tracking camera. The glint 206 may be formed by a reflection of the illuminating light 205 from the eye 104 upon redirecting of the illuminating light 205 to the location of the eye 104.

**[0066]** Turning now to FIG. 4 with further reference to FIG. 3, a method 400 for locating an eye at an eyebox, e.g. determining at least one of a position or orientation of the eye 104 at the eyebox 102 (FIG. 3), includes providing (FIG. 4; 402) illuminating light for illuminating the eye at the eyebox, e.g. using the light source 201 of FIG. 3 to provide the illuminating light 205. A switchable grating structure such as, for example, the switchable grating structure 208 of the near-eye display 300 of FIG. 3 and of the eye tracking system 200 of FIG. 2, is used (FIG. 4; 404) to redirect the illuminating light to a location of the eye at an eyebox. An eye tracking camera is used (406) to obtain an image of the eye at the eyebox.

**[0067]** The method 400 may further include determining (408) the location of the eye at the eyebox from the image obtained by the eye tracking camera e.g. by using suitable calibration and eye image recognition; and causing the switchable grating structure to redirect (410) the illuminating light to the location of the eye at the eyebox. The orientation of the eye at the eyebox may then be determined by detecting (412) a glint of the illuminating light in an image obtained by the eye tracking camera. The glint may be formed by a reflection of the illuminating light from the eye upon redirecting of the illuminating light to the location of the eye.

**[0068]** Embodiments illustrating the usage of switchable gratings in an eye tracker's eye image forming paths will now be considered. Referring to FIG. 5 for a non-limiting illustrative example, a near-eye display 500 includes a lightguide, e.g. a pupil-replicating lightguide 508 in form of a slab of transparent material for propagating image light 521 and tracking light 522 by a series of internal reflections in the slab.

**[0069]** The image light 521 carries an image in angular domain to the user's eye 104 at the eyebox 102. The image light 521 may be formed by an image projector 552, which is similar to the image projector 352 of the near-eye display 300 of FIG. 3. To in-couple the image light 521, the pupil-replicating lightguide 500 may include an in-coupler 514, e.g. an in-coupling grating which may be a switchable grating, for in-coupling the image light 521 into the pupil-replicating lightguide 508. To out-couple the image light 521, the pupil-replicating lightguide 500 may include a switchable out-coupling grating 516. The switchable out-coupling grating 516 out-couples portions 521A of the image light 521 to propagate towards the eyebox 102.

**[0070]** The tracking light 522 carries an image of the eye to an eye tracking camera 512. The tracking light 522 is a light reflected from the eye 104 upon illumination by the illumination light 205, or light from a dedicated wide-field illuminator at a suitable wavelength. The pupil-replicating lightguide 508 may include a switchable tracking grating 515 for redirecting the tracking light to propagate in the pupil-replicating lightguide 508 toward the eye tracking camera 512, and an out-coupler 517, e.g. an out-coupling tracking grating which may also be a switchable grating, for out-coupling the tracking light 522 from the pupil-replicating lightguide 508 into the tracking camera 512.

**[0071]** The pupil-replicating lightguide 508 has a clear aperture 530, defined as an area of the pupil-replicating lightguide 508 (i.e. the area in XY plane in FIG. 5) through which external light 564 may propagate to the eye 104, such that the user's eye 104 may observe outside environment. Both the switchable out-coupling grating 516 and the switchable tracking grating 515 are at least partially disposed in the field of view of the outside environment through the clear aperture 530, such that projections of the switchable out-coupling grating 516 and the switchable tracking grating 515 onto the clear aperture 530 of the pupil-replicating lightguide at least partially overlap one another. The switchable out-coupling grating 516 and the switchable tracking grating 515 may be switched to a state where they are transparent or translucent to the external light 564. Alternatively, these gratings may always be transparent or translucent to the

external light 564.

**[0072]** The switchable out-coupling grating 516 is switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating 516 is above a first threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating 516 below a second threshold. The first threshold may be e.g. at least 10 times higher than the second threshold, or in some embodiments at least 100 times or at least 300 times higher. Similarly, the switchable tracking grating 515 is switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating 515 is above a third threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable tracking grating 515 is below a fourth threshold. The third threshold may be e.g. at least 10 times higher than the fourth threshold, or in some embodiments at least 100 times or at least 300 times higher.

**[0073]** A controller 510 may be operably coupled to the switchable out-coupling grating 516, the switchable tracking grating 515, the image projector 552, and the eye tracking camera 512. Referring to FIG. 6 with further reference to FIG. 5, the controller 510 may be suitably configured, for example programmed with software, firmware, and/or hard-wired, to switch the switchable out-coupling grating 516 to the high-efficiency state and switch the switchable tracking grating 515 to the low-efficiency state during a first time interval $T_1$. During a subsequent second time interval $T_2$, the controller 510 switches the switchable out-coupling grating 516 to the low-efficiency state and the switchable tracking grating 515 to the high-efficiency state. The second time interval $T_2$ may immediately follow the first time interval $T_1$. The next first time interval $T_1$ may immediately follow the second time interval $T_2$, and so on. The second time interval $T_2$, i.e. the time interval when the eye images are obtained, may be much shorter than the first time interval $T_1$, e.g. at least 10 times shorter, at least 100 times shorter, or even at least 300 times shorter.

**[0074]** Providing separate time slots for the image displaying and for the eye tracking functions allows one to lower the energy consumption of the display 500, with the image displaying and eye tracking being performed in a time-sequential manner. For instance, the first time interval $T_1$ may correspond to an image frame displaying time, and the second time interval $T_2$ may correspond to an inter-frame time interval when a new image frame is being loaded into the display's memory. The controller 510 may be configured to cause the image projector 552 to display the image during the

first time interval $T_1$ and to provide no image light 521 during the second time interval $T_2$, i.e. to switch off the image projector 552 during the second time interval $T_2$ to preserve power. During the second time interval $T_2$, the controller 510 may cause the eye tracking camera 512 to obtain the image of the eye 104. The controller 510 may switch the eye illuminating light off during the first time interval $T_1$ to preserve power.

**[0075]** Turning to FIG. 7 with further reference to FIGs. 5 and 6, a method 700 for displaying an image to an eye and tracking the eye includes providing (702) image light carrying an image in angular domain, e.g. using the image projector 552 of FIG. 5 to display the image in angular domain. The image may be provided frame by frame, or may be scanned or rastered pixel by pixel, or by groups of pixels, during a frame period. The image light 521 is propagated (704) in a slab of transparent material, e.g. in the pupil-replicating lightguide 508, by series of internal reflections, e.g. total internal reflections, from the slab surfaces. During a first time interval, which may be equal to the frame period as noted above, an out-coupling grating e.g. the out-coupling grating 516 of the pupil-replicating lightguide 508 (FIG. 5) may be switched to a high-efficiency state (706) to out-couple portions of the image light to propagate towards the eyebox. During a second, subsequent time interval which may be equal to an inter-frame period, a tracking grating may be switched (708) to a high-efficiency state to redirect tracking light carrying an image of the eye towards an eye tracking camera. During this time interval, the out-coupling grating may be switched to a low-efficiency state; and similarly, the tracking grating may be switched to a low-efficiency state during the first time interval. The first and second time intervals may then repeat one after another as indicated by an arrow 710. The out-coupling efficiency of the out-coupling grating may be at least ten times higher in the high efficiency state than in the low-efficiency state, and an out-coupling efficiency of the tracking grating may be at least ten times higher in the high efficiency state than in the low-efficiency state.

**[0076]** Non-limiting examples of switchable / tunable gratings usable in lightguides and displays of this disclosure will now be presented. Referring first to FIG. 8, a tunable liquid crystal (LC) surface-relief grating 800 may be used e.g. in the switchable grating structure 208 of the eye tracking system 200 of FIG. 2, the switchable tracking grating 515, the switchable out-coupling grating 516, the in-coupler 514, and/or the out-coupler 517 of the pupil-replicating lightguide 508 of FIGs. 5 and 6. The tunable LC surface-relief grating 800 includes a first substrate 801 supporting a first conductive layer 811 and a surface-relief grating structure 804 having a plurality of ridges 806 extending

from the first substrate 801 and/or the first conductive layer 811.

**[0077]** A second substrate 802 is spaced apart from the first substrate 801. The second substrate 802 supports a second conductive layer 812. A cell is formed by the first 811 and second 812 conductive layers. The cell is filled with a LC fluid, forming an LC layer 808. The LC layer 808 includes nematic LC molecules 810, which may be oriented by an electric field across the LC layer 808. The electric field may be provided by applying a voltage $V$ to the first 811 and second 812 conductive layers.

**[0078]** The surface-relief grating structure 804 may be formed from a polymer with an isotropic refractive index $n_p$ of about 1.5, for example. The LC fluid has an anisotropic refractive index. For light polarization parallel to a director of the LC fluid, i.e. to the direction of orientation of the nematic LC molecules 810, the LC fluid has an extraordinary refractive index $n_e$, which may be higher than an ordinary refractive index $n_o$ of the LC fluid for light polarization perpendicular to the director. For example, the extraordinary refractive index $n_e$ may be about 1.7, and the ordinary refractive index $n_o$ may be about 1.5, i.e. matched to the refractive index $n_p$ of the surface-relief grating structure 804.

**[0079]** When the voltage $V$ is not applied (left side of FIG. 8), the LC molecules 810 are aligned approximately parallel to the grooves of the surface-relief grating structure 804. At this configuration, a linearly polarized light beam 821 with e-vector oriented along the grooves of the surface-relief grating structure 804 will undergo diffraction, since the surface-relief grating structure 804 will have a non-zero refractive index contrast. When the voltage $V$ is applied (right side of FIG. 8), the LC molecules 810 are aligned approximately perpendicular to the grooves of the surface-relief grating structure 804. At this configuration, a linearly polarized light beam 821 with e-vector oriented along the grooves of the surface-relief grating structure 804 will not undergo diffraction because the surface-relief grating structure 804 will appear to be index-matched and, accordingly, will have a substantially zero refractive index contrast. For the linearly polarized light beam 821 with e-vector oriented perpendicular to the grooves of the surface-relief grating structure 804, no diffraction will occur in either case (i.e. when the voltage is applied and when it is not), because at this polarization of the linearly polarized light beam 821, the surface-relief grating structure 804 are index-matched. Thus, the tunable LC surface-relief grating 800 can be switched on and off (for polarized light) by controlling the voltage across the LC layer 808. Several such gratings with differing pitch / slant angle / refractive index contrast may be used to

switch between several grating configurations. In some embodiments, the surface-relief grating structure 804 may include a birefringent material, as well.

**[0080]** Referring now to FIG. 9A, a Pancharatnam–Berry phase (PBP) LC switchable grating 900 may be used e.g. in the switchable grating structure 208 of the eye tracking system 200 of FIG. 2, the switchable tracking grating 515, the switchable out-coupling grating 516, the in-coupler 514, and/or the out-coupler 517 of the pupil-replicating lightguide 508 of FIGs. 5 and 6. The PBP LC switchable grating 900 of FIG. 9A includes LC molecules 902 in an LC layer 904. The LC molecules 902 are disposed in XY plane at a varying in-plane orientation depending on the X coordinate. The orientation angle $\phi(x)$ of the LC molecules 902 in the PBP LC switchable grating 900 is given by

**[0081]** $\phi(x) = \pi x/\mathrm{T} = \pi x \sin\theta / \lambda_o$ (1)

**[0082]** where $\lambda_o$ is the wavelength of impinging light, T is a pitch of the PBP LC switchable grating 900, and $\theta$ is a diffraction angle given by

**[0083]** $\theta = \sin^{-1}(\lambda_o / \mathrm{T})$ (2)

**[0084]** The azimuthal angle $\phi$ varies continuously across the surface of an LC layer 904 parallel to XY plane as illustrated in FIG. 9B. The variation has a constant period equal to T. The optical phase delay P in the PBP LC grating 900 of FIG. 9A is due to the PBP effect, which manifests $P(x) = 2\phi(x)$ when the optical retardation R of the LC layer 904 is equal to $\lambda/2$.

**[0085]** FIGs. 10A and 10B illustrate the operation of the PBP LC switchable grating 900 of FIG. 9A. The PBP LC switchable grating 900 includes the LC layer 904 (FIG. 9A) disposed between parallel substrates configured for applying an electric field across the LC layer 904. The LC molecules 902 are oriented substantially parallel to the substrates in absence of the electric field, and substantially perpendicular to the substrates in presence of the electric field.

**[0086]** In FIG. 10A, the PBP LC switchable grating 900 is in OFF state, such that its LC molecules 902 (FIGs. 9A, 9B) are disposed predominantly parallel to the substrate plane, that is, parallel to XY plane in FIG. 10A. When an incoming light beam 1015 is left-circular polarized (LCP), the PBP LC switchable grating 900 redirects the light beam 1015 upwards by a pre-determined non-zero angle, and the beam 1015 becomes right-circular polarized (RCP). The RCP deflected beam 1015 is shown with solid lines. When the incoming light beam 1015 is right-circular polarized (RCP), the

PBP LC switchable grating 900 redirects the beam 1015 downwards by a pre-determined non-zero angle, and the beam 1015 becomes left-circular polarized (LCP). The LCP deflected beam 1015 is shown with dashed lines. Applying a voltage V to the PBP LC switchable grating 900 reorients the LC molecules along Z-axis, i.e. perpendicular to the substrate plane as shown in FIG. 10B. At this orientation of the LC molecules 902, the PBP structure is erased, and the light beam 1015 retains its original direction, whether it is LCP or RCP. Thus, the active PBP LC grating 900 is a tunable grating, i.e. it has a variable beam steering property. Furthermore, the operation of the active PBP LC grating 900 may be controlled by controlling the polarization state of the impinging light beam 1015.

**[0087]** Turning to FIG. 11A, a polarization volume hologram (PVH) grating 1100 may be used e.g. in the switchable grating structure 208 of the eye tracking system 200 of FIG. 2, the switchable tracking grating 515, the switchable out-coupling grating 516, the in-coupler 514, and/or the out-coupler 517 of the pupil-replicating lightguide 508 of FIGs. 5 and 6. The PVH grating 1100 of FIG. 11A includes an LC layer 1104 bound by opposed top 1105 and bottom 1106 parallel surfaces. The LC layer 1104 may include an LC fluid containing rod-like LC molecules 1107 with positive dielectric anisotropy, i.e. nematic LC molecules. A chiral dopant may be added to the LC fluid, causing the LC molecules in the LC fluid to self-organize into a periodic helical configuration including helical structures 1108 extending between the top 1105 and bottom 1106 parallel surfaces of the LC layer 1104. Such a configuration of the LC molecules 1107, termed herein a cholesteric configuration, includes a plurality of helical periods ***p***, e.g. at least two, at least five, at least ten, at least twenty, or at least fifty helical periods ***p*** between the top 1105 and bottom 1106 parallel surfaces of the LC layer 1104.

**[0088]** Boundary LC molecules 1107b at the top surface 1105 of the LC layer 1104 may be oriented at an angle to the top surface 1105. The boundary LC molecules 1107b may have a spatially varying azimuthal angle, e.g. linearly varying along X-axis parallel to the top surface 1105, as shown in FIG. 11A. To that end, an alignment layer 1112 may be provided at the top surface 1105 of the LC layer 1104. The alignment layer 1112 may be configured to provide the desired orientation pattern of the boundary LC molecules 1107b, such as the linear dependence of the azimuthal angle on the X-coordinate. A pattern of spatially varying polarization directions of the UV light may be selected to match a desired orientation pattern of the boundary LC molecules 1107b

at the top surface 1105 and/or the bottom surface 1106 of the LC layer 1104. When the alignment layer 1112 is coated with the cholesteric LC fluid, the boundary LC molecules 1107b are oriented along the photopolymerized chains of the alignment layer 1112, thus adopting the desired surface orientation pattern. Adjacent LC molecules adopt helical patterns extending from the top 1105 to the bottom 1106 surfaces of the LC layer 1104, as shown.

**[0089]** The boundary LC molecules 1107b define relative phases of the helical structures 1108 having the helical period $p$. The helical structures 1108 form a volume grating comprising helical fringes 1114 tilted at an angle $\phi$, as shown in FIG. 11A. The steepness of the tilt angle $\phi$ depends on the rate of variation of the azimuthal angle of the boundary LC molecules 1107b at the top surface 1105 and $p$. Thus, the tilt angle $\phi$ is determined by the surface alignment pattern of the boundary LC molecules 1107b at the alignment layer 1112. The volume grating has a period $\Lambda_x$ along X-axis and $\Lambda_y$ along Y-axis. In some embodiments, the periodic helical structures 1108 of the LC molecules 1107 may be polymer-stabilized by mixing in a stabilizing polymer into the LC fluid, and curing (polymerizing) the stabilizing polymer.

**[0090]** The helical nature of the fringes 1114 of the volume grating makes the PVH grating 1100 preferably responsive to light of polarization having one particular handedness, e.g. left- or right- circular polarization, while being substantially non-responsive to light of the opposite handedness of polarization. Thus, the helical fringes 1114 make the PVH grating 1100 polarization-selective, causing the PVH grating 1100 to diffract light of only one handedness of circular polarization. This is illustrated in FIG. 11B, which shows a light beam 1120 impinging onto the PVH grating 1100. The light beam 1120 includes a left circular polarized (LCP) beam component 1121 and a right circular polarized (RCP) beam component 1122. The LCP beam component 1121 propagates through the PVH grating 1100 substantially without diffraction. Herein, the term "substantially without diffraction" means that, even though an insignificant portion of the beam (the LCP beam component 1121 in this case) might diffract, the portion of the diffracted light energy is so small that it does not impact the intended performance of the PVH grating 1100. The RCP beam component 1122 of the light beam 1120 undergoes diffraction, producing a diffracted beam 1122'. The polarization selectivity of the PVH grating 1100 results from the effective refractive index of the grating being dependent on the relationship between the handedness, or chirality, of the

impinging light beam and the handedness, or chirality, of the grating fringes 1114. Changing the handedness of the impinging light may be used to switch the performance of the PVH grating 1100. The PVH grating 1100 may also be made switchable or tunable (both terms are used interchangeably in this specification) by applying voltage to the LC layer 1104, which distorts or erases the above-described helical structure. It is further noted that sensitivity of the PVH 1100 to right circular polarized light in particular is only meant as an illustrative example. When the handedness of the helical fringes 1114 is reversed, the PVH 1100 may be made sensitive to left circular polarized light. Thus, the operation of the PVH 1100 may be controlled by controlling the polarization state of the impinging light beam 1120. Furthermore, in some embodiments the PVH 1100 may be made tunable by application of electric field across the LC layer 1104, which erases the periodic helical structures 1108.

**[0091]** Referring now to FIGs. 12A and 12B, a fluidic grating 1200 may be used e.g. in the switchable grating structure 208 of the eye tracking system 200 of FIG. 2, the switchable tracking grating 515, the switchable out-coupling grating 516, the in-coupler 514, and/or the out-coupler 517 of the pupil-replicating lightguide 508 of FIGs. 5 and 6. The fluidic grating 1200 includes first 1201 and second 1202 immiscible fluids separated by an inter-fluid boundary 1203. One of the fluids may be a hydrophobic fluid such as oil, e.g. silicone oil, while the other fluid may be water-based. One of the first 1201 and second 1202 fluids may be a gas in some embodiments. The first 1201 and second 1202 fluids may be contained in a cell formed by first 1211 and second 1212 substrates supporting first 1221 and second 1222 electrode structures. The first 1221 and/or second 1222 electrode structures may be at least partially transparent, absorptive, and/or reflective.

**[0092]** At least one of the first 1221 and second 1222 electrode structures may be patterned for imposing a spatially variant electric field onto the 1201 and second 1202 fluids. For example, in 12A and 12B, the first electrode 1221 is patterned, and the second electrodes 1222 is not patterned, i.e. the second electrodes 1222 is a backplane electrode. In the embodiment shown, both the first 1221 and second 1222 electrodes are substantially transparent. For example, the first 1221 and second 1222 electrodes may be indium tin oxide (ITO) electrodes. The individual portions of a patterned electrode may be individually addressable. In some embodiments, the patterned electrode 1221 may be replaced with a continuous, non-patterned electrode coupled to a patterned dielectric layer for creating a spatially non-uniform electric field across the

first 1201 and second 1202 fluids.

**[0093]** FIG. 12A shows the fluidic grating 1200 in a non-driven state when no electric field is applied across the inter-fluid boundary 1203. When no electric field is present, the inter-fluid boundary 1203 is straight and smooth; accordingly, a light beam 1205 impinging onto the fluidic grating 1200 does not diffract, propagating right through as illustrated. FIG. 12B shows the fluidic grating 1200 in a driven state when a voltage $V$ is applied between the first 1221 and second 1222 electrodes, producing a spatially variant electric field across the first 1201 and second 1202 fluids separated by the inter-fluid boundary 1203. The application of the spatially variant electric field causes the inter-fluid boundary 1203 to distort as illustrated in FIG. 12B, forming a periodic variation of effective refractive index, i.e. a surface-relief diffraction grating. The light beam 1205 impinging onto the fluidic grating 1200 will diffract, forming first 1231 and second 1232 diffracted sub-beams. By varying the amplitude of the applied voltage $V$, the strength of the fluidic grating 1200 may be varied. By applying different patterns of the electric field e.g. with individually addressable sub-electrodes or pixels of the first electrode 1221, the grating period and, accordingly, the diffraction angle, may be varied. More generally, varying the effective voltage between separate sub-electrodes or pixels of the first electrode 1221 may result in a three-dimensional conformal change of the fluidic interface i.e. the inter-fluid boundary 1203 inside the fluidic volume to impart a desired optical response to the fluidic grating 1200. The applied voltage pattern may be pre-biased to compensate or offset gravity effects, i.e. gravity-caused distortions of the inter-fluid boundary 1203.

**[0094]** The thickness of the first 1221 and second 1222 electrodes may be e.g. between 10nm and 50nm. The materials of the first 1221 and second 1222 electrodes besides ITO may be e.g. indium zinc oxide (IZO), zinc oxide (ZO), indium oxide (IO), tin oxide (TO), indium gallium zinc oxide (IGZO), etc. The first 1201 and second 1202 fluids may have a refractive index difference of at least 0.1, and may be as high as 0.2 and higher. One of the first 1201 or second 1202 fluids may include polyphenylether, 1,3-bis(phenylthio)benzene, etc. The first 1211 and/or second 1212 substrates may include e.g. fused silica, quartz, sapphire, etc. The first 1211 and/or second 1212 substrates may be straight or curved, and may include vias and other electrical interconnects. The applied voltage may be varied in amplitude and/or duty cycle when applied at a frequency of between 100Hz and 100kHz. The applied voltage can change polarity and/or be bipolar. Individual first 1201 and/r second 1202 fluid layers may

have a thickness of between 0.5-5 micrometers, more preferably between 0.5-2 micrometer.

**[0095]** To separate the first 1201 and second 1202 fluids, surfactants containing one hydrophilic end functional group and one hydrophobic end functional group may be used. The examples of a hydrophilic end functional group are hydroxyl, carboxyl, carbonyl, amino, phosphate, sulfhydryl. The hydrophilic functional groups may also be anionic groups such as sulfate, sulfonate, carboxylates, phosphates, for example. Non-limiting examples of a hydrophobic end functional group are aliphatic groups, aromatic groups, fluorinated groups. For example, when polyphenyl thioether and fluorinated fluid may be selected as a fluid pair, a surfactant containing aromatic end group and fluronirated end group may be used. When phenyl silicone oil and water are selected as the fluid pair, a surfactant containing aromatic end group and hydroxyl (or amino, or ionic) end group may be used. These are only non-limiting examples.

**[0096]** Referring to FIG. 13A, a pupil-replicating lightguide 1300A of this disclosure includes a body 1306A having two portions, a substrate 1328 for propagating image light 1304, and a volume-wave acoustic actuator 1330A mechanically coupled at a side of the substrate 1328 joining its top 1315 and bottom 1316 surfaces. In the embodiment shown, the volume-wave acoustic actuator 1330A includes an electrically responsive layer 1332A, e.g. a piezoelectric layer, disposed between electrodes 1307A,1308A. In operation, an electrical signal at a high frequency, typically in the range of 1MHz to 100MHz or higher, is applied to the electrodes 1307A,1308A causing the electrically responsive layer 1332A to oscillate, typically at a frequency of a mechanical resonance of the electrically responsive layer 1332A. The oscillating thickness of the electrically responsive layer 1332A creates a volume acoustic wave 1334A propagating in the substrate 1328 in a direction 1335, i.e. along the X-axis. The volume acoustic wave 1334A modulates the refractive index of the substrate 1328 due to the effect of photoelasticity. The modulated refractive index creates a diffraction grating that out-couples portions 1312, 1313 of the image light 1304 from the pupil-replicating lightguide 1300A. By changing the strength of the electric signal applied to the volume-wave acoustic actuator 1330A, the strength of the out-coupling grating may be changed. The out-coupling grating may be switched ON and OFF by switching ON and OFF the oscillating electric signal. The grating period may be changed by changing the frequency of the oscillating electric signal. In some embodiments, an acoustic wave terminator 1336A can be coupled to an opposite side of the substrate 1328 to absorb

the volume acoustic wave 1334A and thus prevent a standing acoustic wave formation in the substrate 1328. The pupil-replicating lightguide 1300A may be used e.g. in the switchable grating structure 208 of the eye tracking system 200 of FIG. 2, the switchable tracking grating 515, the switchable out-coupling grating 516, the in-coupler 514, and/or the out-coupler 517 of the pupil-replicating lightguide 508 of FIGs. 5 and 6.

**[0097]** Turning to FIG. 13B, a pupil-replicating waveguide 1300B of the present disclosure includes a waveguide body 1306B having two portions, the substrate 1328 for propagating the beam of image light 1304, and a surface-wave acoustic actuator 1330B mechanically coupled at the top surface 1315. Alternatively, the surface-wave acoustic actuator 1330B may also be coupled at the bottom surface 1316. In the embodiment shown, the surface-wave acoustic actuator 1330B includes an electrically responsive layer 1332B, e.g. a piezoelectric layer, disposed between electrodes 1307B,1308B. In operation, an electrical signal at a high frequency, typically in the range of 1MHz to 100MHz or higher, is applied to the electrodes 1307B,1308B causing the electrically responsive layer 1332B to oscillate. The oscillation of the electrically responsive layer 1332A creates a surface acoustic wave 1334B propagating in the substrate 1328 in the direction 1335, i.e. along the X-axis. The surface acoustic wave 1334B forms a diffraction grating that out-couples the portions 1312, 1313 of the image light 1304 from the pupil-replicating lightguide 1300B. By changing the strength of the electric signal applied to the surface-wave acoustic actuator 1330B, the strength of the surface grating may be changed. The surface grating may be switched ON and OFF by switching ON and OFF the oscillating electric signal. The grating period may be changed by changing the frequency of the oscillating electric signal. In some embodiments, an acoustic wave terminator 1336B can be coupled to an opposite side of the substrate 1328 at the same surface, i.e. at the top surface 1315 in FIG. 13B, to absorb the surface acoustic wave 1334B and thus prevent a standing acoustic wave formation. The pupil-replicating lightguide 1300B may be used e.g. in the switchable grating structure 208 of the eye tracking system 200 of FIG. 2, the switchable tracking grating 515, the switchable out-coupling grating 516, the in-coupler 514, and/or the out-coupler 517 of the pupil-replicating lightguide 508 of FIGs. 5 and 6.

**[0098]** Some switchable gratings include a material with tunable refractive index. By way of a non-limiting example, a holographic polymer-dispersed liquid crystal (H-PDLC) grating may be manufactured by causing interference between two coherent

laser beams in a photosensitive monomer/liquid crystal (LC) mixture contained between two substrates coated with a conductive layer. Upon irradiation, a photoinitiator contained within the mixture initiates a free-radical reaction, causing the monomer to polymerize. As the polymer network grows, the mixture phase separates into polymer-rich and liquid-crystal rich regions. The refractive index modulation between the two phases causes light passing through the cell to be scattered in the case of traditional PDLC or diffracted in the case of H-PDLC. When an electric field is applied across the cell, the index modulation is removed and light passing through the cell is unaffected. This is described in an article entitled "Electrically Switchable Bragg Gratings from Liquid Crystal/Polymer Composites" by Pogue et al., Applied Spectroscopy, v. 54 No. 1, 2000, which is incorporated herein by reference in its entirety.

**[0099]** Tunable or switchable gratings with a variable grating period may be produced e.g. by using flexoelectric LC. For LCs with a non-zero flexoelectric coefficient difference ($e1–e3$) and low dielectric anisotropy, electric fields exceeding certain threshold values result in transitions from the homogeneous planar state to a spatially periodic one. Field-induced grating is characterized by rotation of the LC director about the alignment axis with the wavevector of the grating oriented perpendicular to the initial alignment direction. The rotation sign is defined by both the electric field vector and the sign of the ($e1–e3$) difference. The wavenumber characterizing the field-induced periodicity is increased linearly with the applied voltage starting from a threshold value of about $\pi/d$, where $d$ is the thickness of the layer. A description of flexoelectric LC gratings may be found e.g. in an article entitled "Dynamic and Photonic Properties of Field-Induced Gratings in Flexoelectric LC Layers" by Palto in Crystals 2021, 11, 894, which is incorporated herein by reference in its entirety.

**[00100]** Tunable gratings with a variable grating period or a slant angle may be provided e.g. by using helicoidal LC. Tunable gratings with helicoidal LCs have been described e.g. in an article entitled "Electrooptic Response of Chiral Nematic Liquid Crystals with Oblique Helicoidal Director" by Xiang et al. Phys. Rev. Lett. 112, 217801, 2014, which is incorporated herein by reference in its entirety.

**[00101]** For gratings exhibiting strong wavelength dependence of grating efficiency, several gratings, e.g. several volumetric Bragg grating (VBG) gratings, may be provided in the lightguide. The gratings that diffract light at any given moment of time

may be switched by switching the VBG grating on and off, and/or by switching the wavelength of the light propagating in the waveguide.

**[00102]** Referring now to FIG. 14, a near-eye display 1400 is an example implementation of the near-eye display 300 of FIG. 3. The near-eye display 1400 includes a frame 1403 supporting, for each eye: an image projector 1430 for providing an image light beam carrying an image in angular domain, a pupil-replicating lightguide 1406 including any of the waveguides disclosed herein, for providing multiple offset portions of the image light beam to spread the image in angular domain across an eyebox 1412, and a an eye tracking camera 1404. The purpose of the eye tracking cameras 1404 is to determine position and/or orientation of both eyes of the user. The near-eye display 1400 may include a light source 1401 coupled to a switchable grating structure 1408 for redirecting the illuminating light to the eye location as was explained above with reference to FIGs. 2 and 3.

**[00103]** Turning to FIG. 15, an HMD 1500 is a non-limiting illustrative example of an AR/VR wearable display system which encloses the user's face, for a greater degree of immersion into the AR/VR environment. The HMD 1500 is an example implementation of the near-eye display 300 of FIG. 3 and the near-eye display 500 of FIG. 5. The HMD 1500 may generate the entirely virtual 3D imagery. The HMD 1500 may include a front body 1502 and a band 1504 that can be secured around the user's head. The front body 1502 is configured for placement in front of eyes of a user in a reliable and comfortable manner. A display system 1580 may be disposed in the front body 1502 for presenting AR/VR imagery to the user. The display system 1580 may include any of the display devices and waveguides disclosed herein. Sides 1506 of the front body 1502 may be opaque or transparent.

**[00104]** In some embodiments, the front body 1502 includes locators 1508 and an inertial measurement unit (IMU) 1510 for tracking acceleration of the HMD 1500, and position sensors 1512 for tracking position of the HMD 1500. The IMU 1510 is an electronic device that generates data indicating a position of the HMD 1500 based on measurement signals received from one or more of position sensors 1512, which generate one or more measurement signals in response to motion of the HMD 1500. Examples of position sensors 1512 include: one or more accelerometers, one or more gyroscopes, one or more magnetometers, another suitable type of sensor that detects motion, a type of sensor used for error correction of the IMU 1510, or some combination thereof. The position sensors 1512 may be located external to the IMU

1510, internal to the IMU 1510, or some combination thereof.

**[00105]** The locators 1508 are traced by an external imaging device of a virtual reality system, such that the virtual reality system can track the location and orientation of the entire HMD 1500. Information generated by the IMU 1510 and the position sensors 1512 may be compared with the position and orientation obtained by tracking the locators 1508, for improved tracking accuracy of position and orientation of the HMD 1500. Accurate position and orientation is important for presenting appropriate virtual scenery to the user as the latter moves and turns in 3D space.

**[00106]** The HMD 1500 may further include a depth camera assembly (DCA) 1511, which captures data describing depth information of a local area surrounding some or all of the HMD 1500. The depth information may be compared with the information from the IMU 1510, for better accuracy of determination of position and orientation of the HMD 1500 in 3D space.

**[00107]** The HMD 1500 may further include an eye tracking system 1514 for determining orientation and position of user's eyes in real time. The obtained position and orientation of the eyes also allows the HMD 1500 to determine the gaze direction of the user and to adjust the image generated by the display system 1580 accordingly. The determined gaze direction and vergence angle may be used to adjust the display system 1580 to reduce the vergence-accommodation conflict. The direction and vergence may also be used for displays' exit pupil steering as disclosed herein. Furthermore, the determined vergence and gaze angles may be used for interaction with the user, highlighting objects, bringing objects to the foreground, creating additional objects or pointers, etc. An audio system may also be provided including e.g. a set of small speakers built into the front body 1502.

**[00108]** Embodiments of the present disclosure may include, or be implemented in conjunction with, an artificial reality system. An artificial reality system adjusts sensory information about outside world obtained through the senses such as visual information, audio, touch (somatosensation) information, acceleration, balance, etc., in some manner before presentation to a user. By way of non-limiting examples, artificial reality may include virtual reality (VR), augmented reality (AR), mixed reality (MR), hybrid reality, or some combination and/or derivatives thereof. Artificial reality content may include entirely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, somatic or haptic feedback, or some combination thereof. Any of this content may be

presented in a single channel or in multiple channels, such as in a stereo video that produces a three-dimensional effect to the viewer. Furthermore, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in artificial reality and/or are otherwise used in (e.g., perform activities in) artificial reality. The artificial reality system that provides the artificial reality content may be implemented on various platforms, including a wearable display such as an HMD connected to a host computer system, a standalone HMD, a near-eye display having a form factor of eyeglasses, a mobile device or computing system, or any other hardware platform capable of providing artificial reality content to one or more viewers.

**[00109]** The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, other various embodiments and modifications, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such other embodiments and modifications are intended to fall within the scope of the present disclosure. Further, although the present disclosure has been described herein in the context of a particular implementation in a particular environment for a particular purpose, those of ordinary skill in the art will recognize that its usefulness is not limited thereto and that the present disclosure may be beneficially implemented in any number of environments for any number of purposes. Accordingly, the claims set forth below should be construed in view of the full breadth of the present disclosure as described herein.

**What is claimed is:**

1. A near-eye display comprising:

an image projector for providing image light carrying an image in angular domain to an eye at an eyebox of the near-eye display;

an eye tracking camera for receiving tracking light carrying an image of the eye at the eyebox; and

a lightguide coupled to the image projector and the eye tracking camera, the lightguide comprising:

a slab of transparent material for propagating the image light and the tracking light therein;

a switchable out-coupling grating for out-coupling portions of the image light to propagate towards the eyebox; and

a switchable tracking grating for redirecting the tracking light towards the eye tracking camera.

2. The near-eye display of claim 1, wherein:

the slab is configured to transmit external light to the eyebox, providing a field of view of outside environment to the eye; and

both the switchable out-coupling grating and the switchable tracking grating are at least partially disposed in the field of view.

3. The near-eye display of claim 1, wherein:

the switchable out-coupling grating is switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating is above a first threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating below a second threshold; and

the switchable tracking grating is switchable between a high-efficiency state, in which an out-coupling efficiency of the switchable out-coupling grating is above a third threshold, and a low-efficiency state, in which an out-coupling efficiency of the switchable tracking grating is below a fourth threshold.

4. The near-eye display of claim 3, wherein the first threshold is at least 10 times higher than the second threshold, and the third threshold is at least 10 times higher than the fourth threshold.

5. The near-eye display of claim 3, further comprising a controller operably coupled to the switchable out-coupling grating and the switchable tracking grating and configured to:

switch the switchable out-coupling grating to the high-efficiency state and switch the

switchable tracking grating to the low-efficiency state during a first time interval; and

switch the switchable out-coupling grating to the low-efficiency state and switch the switchable tracking grating to the high-efficiency state during a second, subsequent time interval.

6. The near-eye display of claim 5, wherein the controller is operably coupled to the image projector and is configured to cause the image projector to display the image in angular domain during the first time interval.

7. The near-eye display of claim 5, wherein the controller is operably coupled to the eye tracking camera and is configured to cause the eye tracking camera to obtain the image of the eye during the second time interval.

8. The near-eye display of claim 1, wherein:

the lightguide is a pupil-replicating lightguide for propagating the image light and the tracking light by a series of internal reflections in the slab, wherein the tracking light is in-coupled into the slab by the switchable tracking grating, the pupil-replicating lightguide further comprising:

an in-coupling grating for in-coupling the image light provided by the image projector into the slab; and

an out-coupling tracking grating for out-coupling at least a portion of the tracking light from the slab and towards the eye tracking camera.

9. The near-eye display of claim 8, wherein the in-coupling grating is switchable, and wherein the out-coupling tracking grating is switchable.

10. The near-eye display of claim 1, wherein at least one of the switchable out-coupling grating or the switchable tracking grating comprises a switchable polarization volume hologram (PVH) grating.

11. The near-eye display of claim 1, and any one of:

a) wherein at least one of the switchable out-coupling grating or the switchable tracking grating comprises a switchable Pancharatnam–Berry phase (PBP) liquid crystal (LC) grating; or

b) wherein at least one of the switchable out-coupling grating or the switchable tracking grating comprises a switchable liquid crystal (LC) surface relief grating; or

c) wherein at least one of the switchable out-coupling grating or the switchable tracking grating comprises a fluidic grating.

12. A method for displaying an image to an eye and tracking the eye, the method comprising:

providing image light carrying an image in angular domain;

propagating the image light in a slab of transparent material;

during a first time interval, switching an out-coupling grating to a high-efficiency state to out-couple portions of the image light towards an eyebox; and

during a second, subsequent time interval, switching a tracking grating to a high-efficiency state to redirect tracking light carrying an image of the eye towards an eye tracking camera.

13. The method of claim 12, and any one of:

a) further comprising using an image projector to display the image in angular domain during the first time interval; or

b) further comprising switching the out-coupling grating to a low-efficiency state during the second time interval, and switching the tracking grating to a low-efficiency state during the first time interval, in which case optionally wherein an out-coupling efficiency of the out-coupling grating is at least ten times higher in the high efficiency state than in the low-efficiency state, and wherein an out-coupling efficiency of the tracking grating is at least ten times higher in the high efficiency state than in the low-efficiency state.

14. A pupil-replicating lightguide comprising:

a slab of transparent material for propagating image light and tracking light, wherein in operation, the image light carries an image in angular domain to a user's eye at an eyebox, and the tracking light carries an image of the eye to an eye tracking camera;

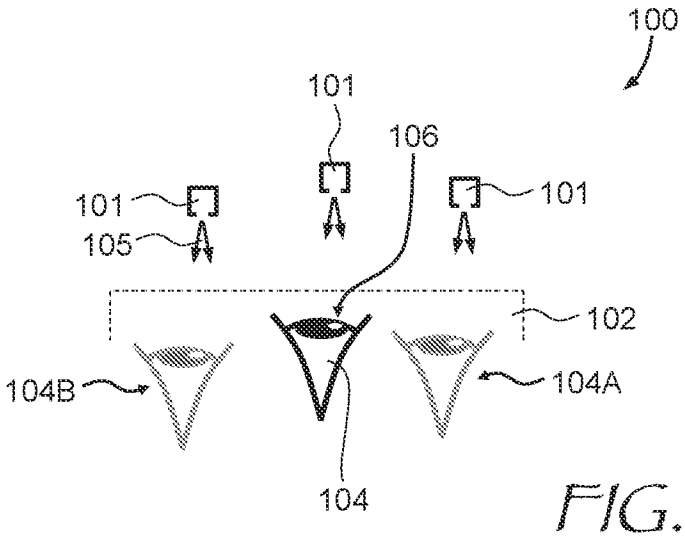
a switchable out-coupling grating for out-coupling portions of the image light to propagate towards the eyebox; and

a switchable tracking grating for redirecting the tracking light towards the eye tracking camera.

15. The pupil-replicating lightguide of claim 14 and any one of:

a) wherein projections of the switchable out-coupling grating and the switchable tracking grating onto a clear aperture of the pupil-replicating lightguide overlap one another; or

b) wherein at least one of the switchable out-coupling grating or the switchable tracking grating comprises at least one of: a switchable polarization volume hologram (PVH) grating; a switchable Pancharatnam–Berry phase (PBP) liquid crystal (LC) grating; a switchable liquid crystal (LC) surface relief grating; or a fluidic grating.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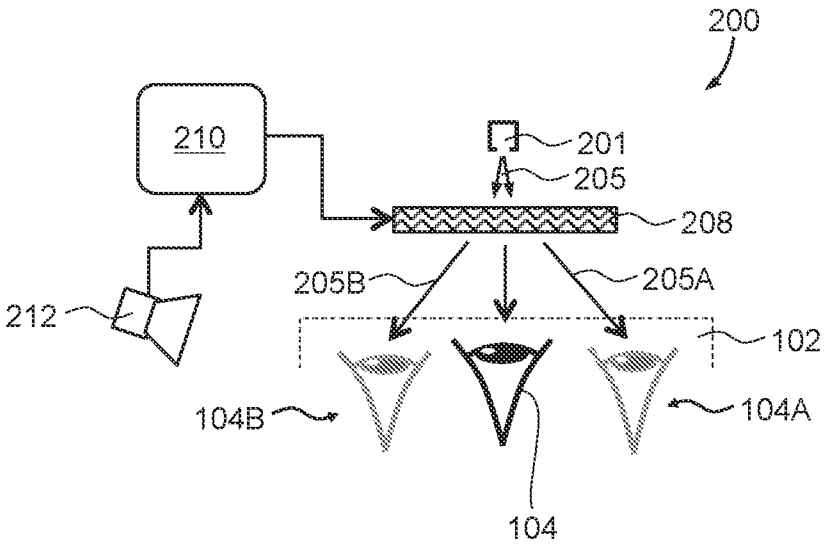
104B
104A
104

FIG. 1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104

FIG. 2

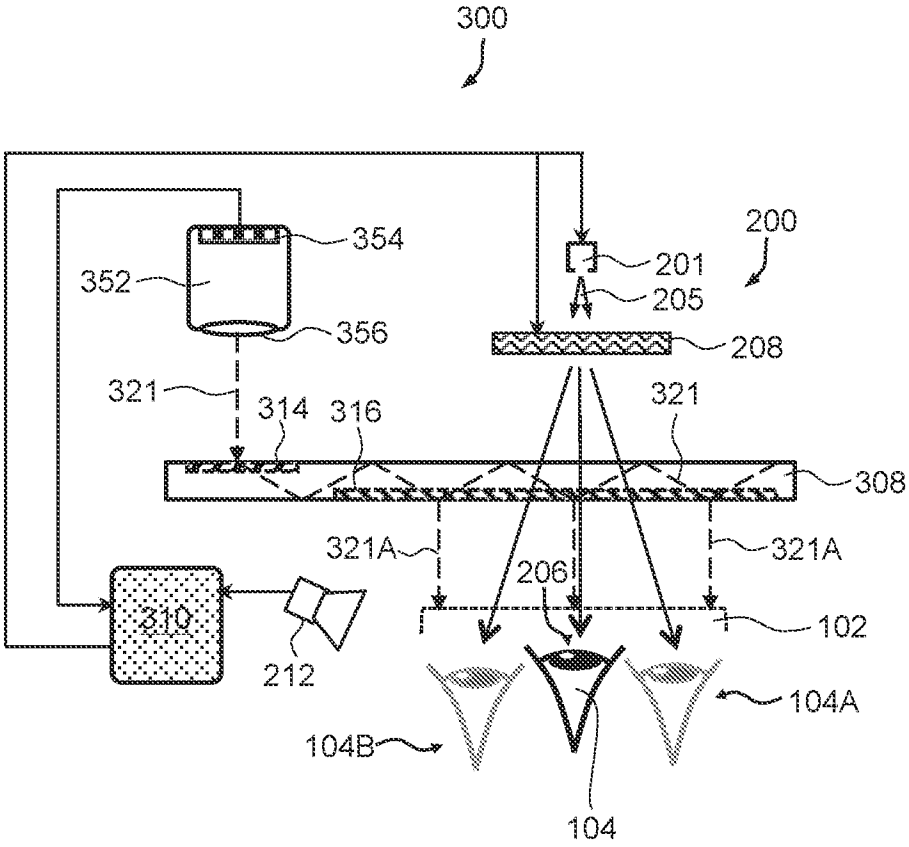
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FIG. 3

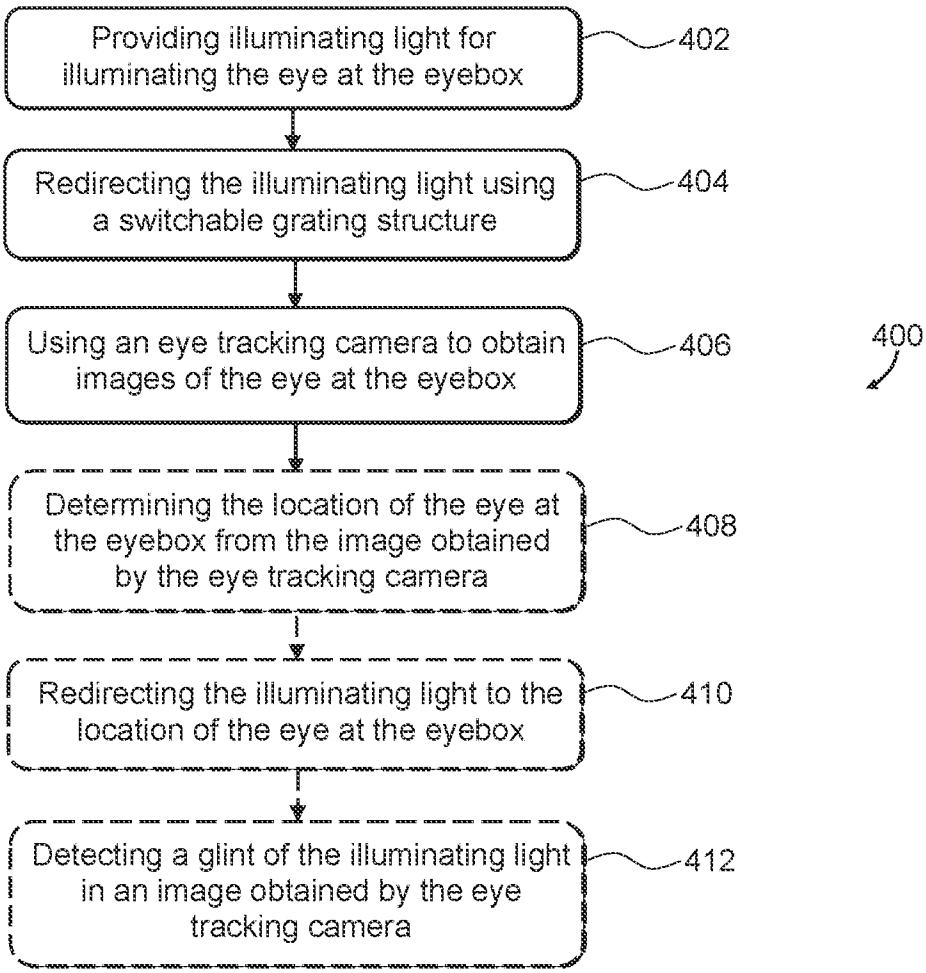
Providing illuminating light for illuminating the eye at the eyebox
402
Redirecting the illuminating light using a switchable grating structure
404
Using an eye tracking camera to obtain images of the eye at the eyebox
406
400
Determining the location of the eye at the eyebox from the image obtained by the eye tracking camera
408
Redirecting the illuminating light to the location of the eye at the eyebox
410
Detecting a glint of the illuminating light in an image obtained by the eye tracking camera
412

FIG. 4

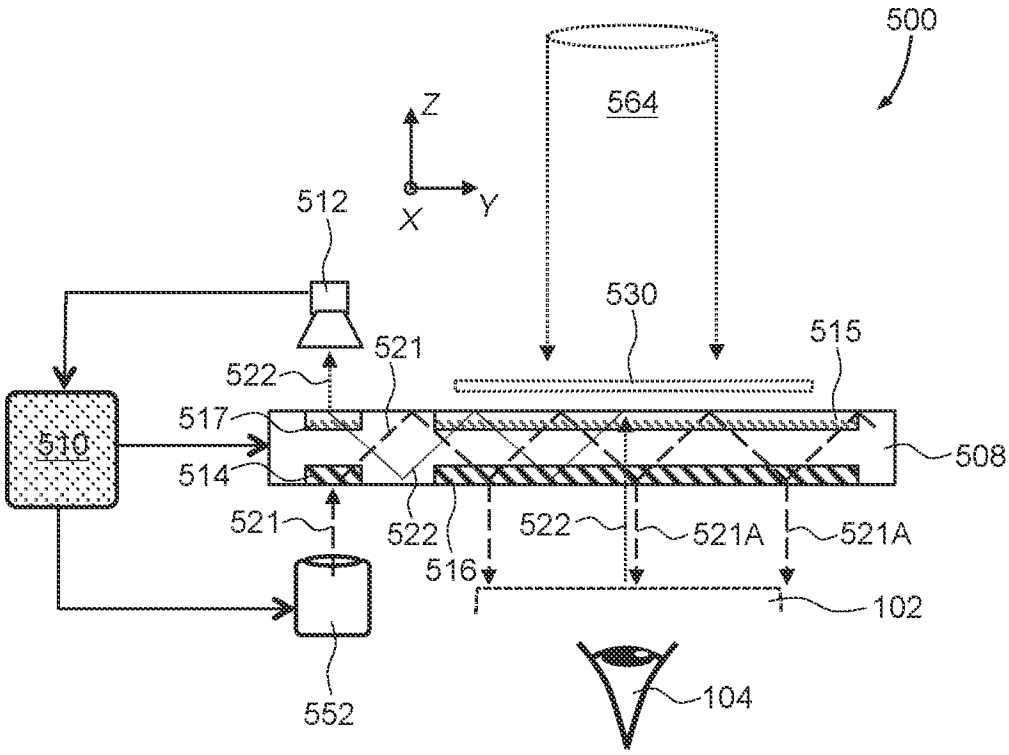
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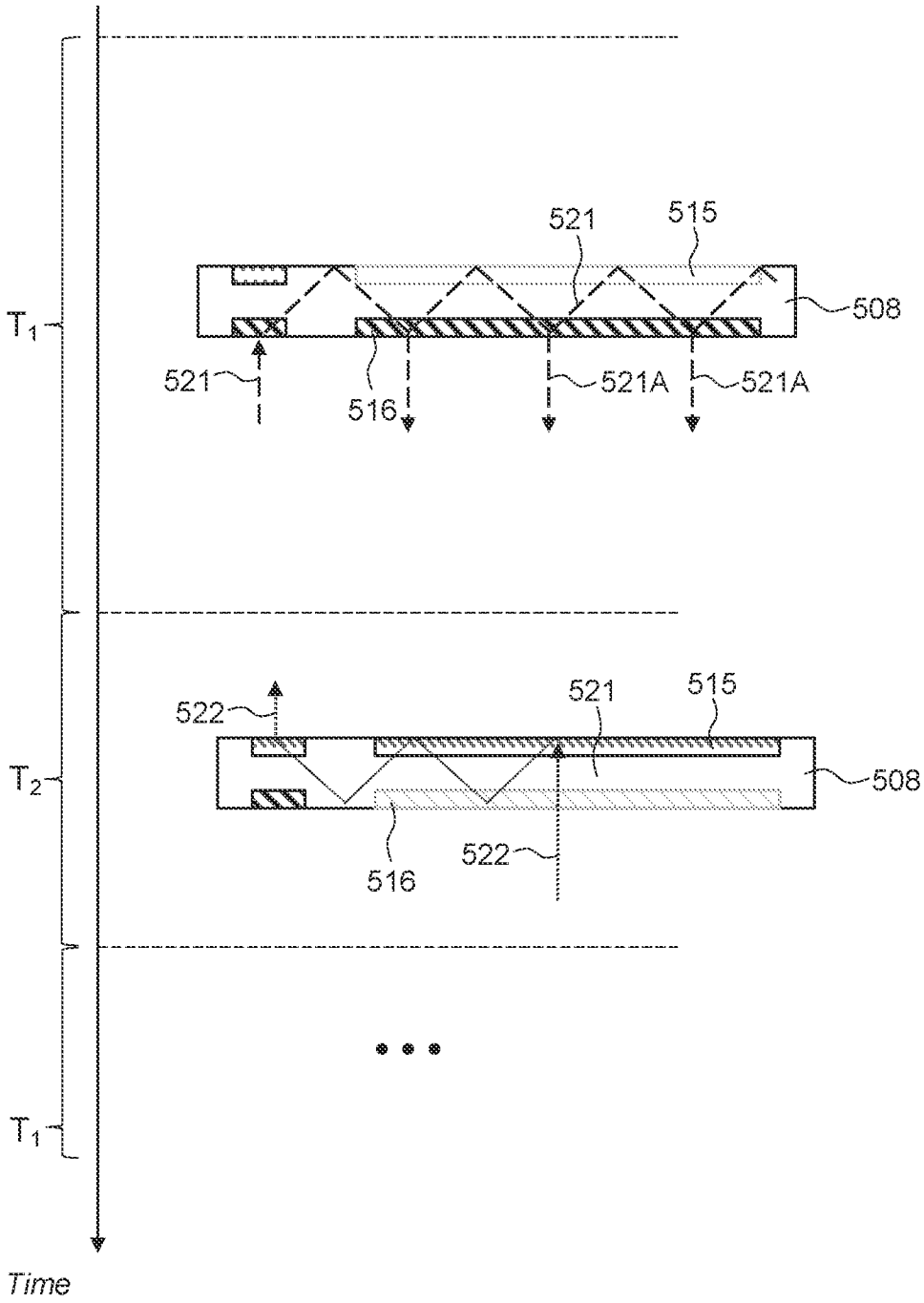
FIG. 5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521A
521A
T2
522
521
515
508
516
522
T1
Time

FIG. 6

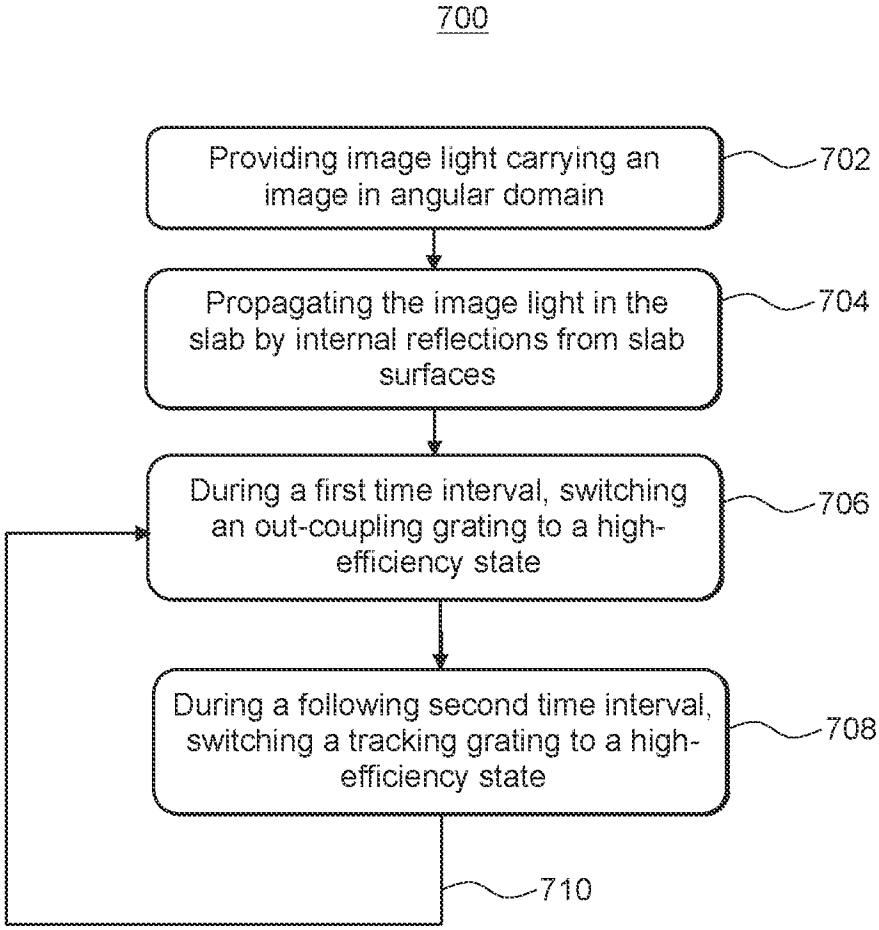
700
Providing image light carrying an image in angular domain
702
Propagating the image light in the slab by internal reflections from slab surfaces
704
During a first time interval, switching an out-coupling grating to a high-efficiency state
706
During a following second time interval, switching a tracking grating to a high-efficiency state
708
710

FIG. 7

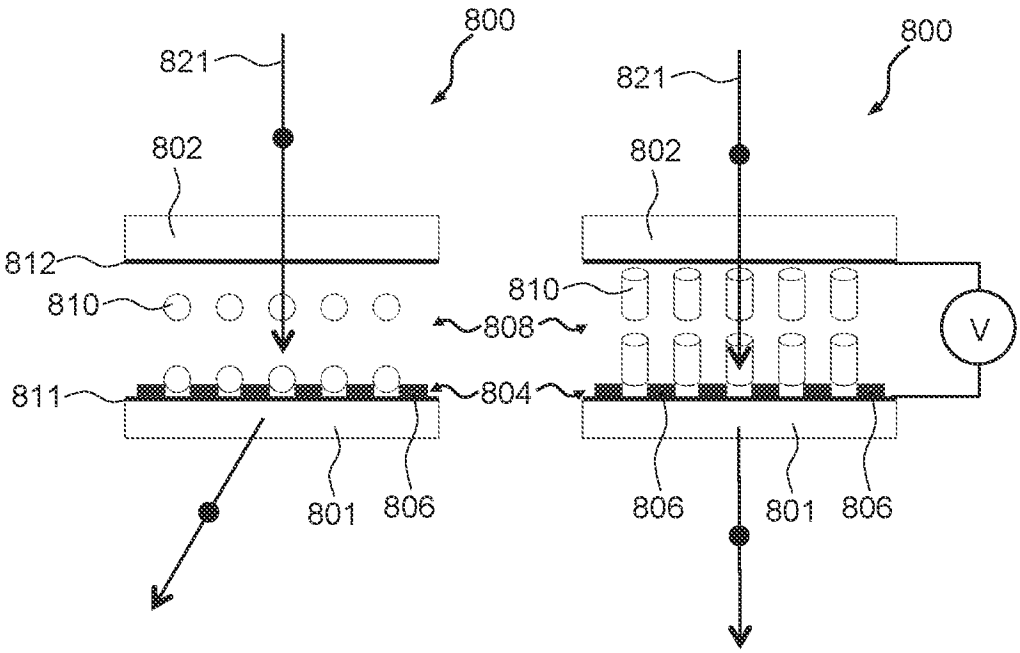
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FIG. 8

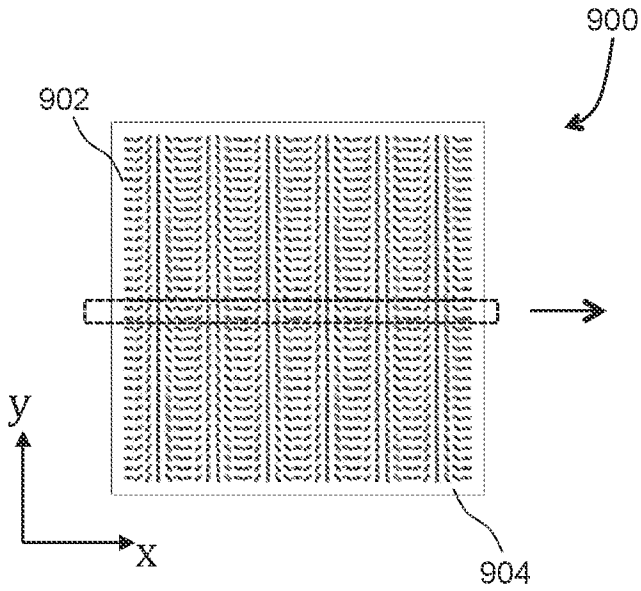


FIG. 9A

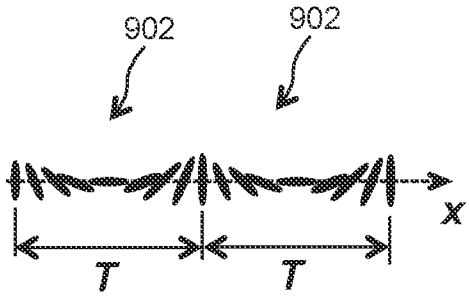


FIG. 9B

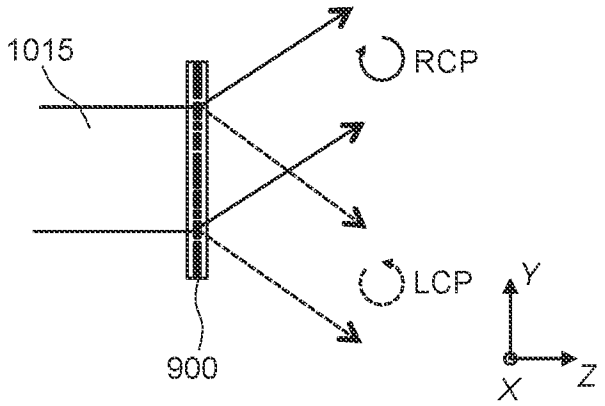


FIG. 10A

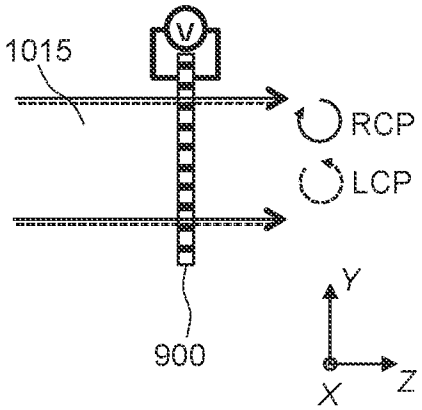


FIG. 10B

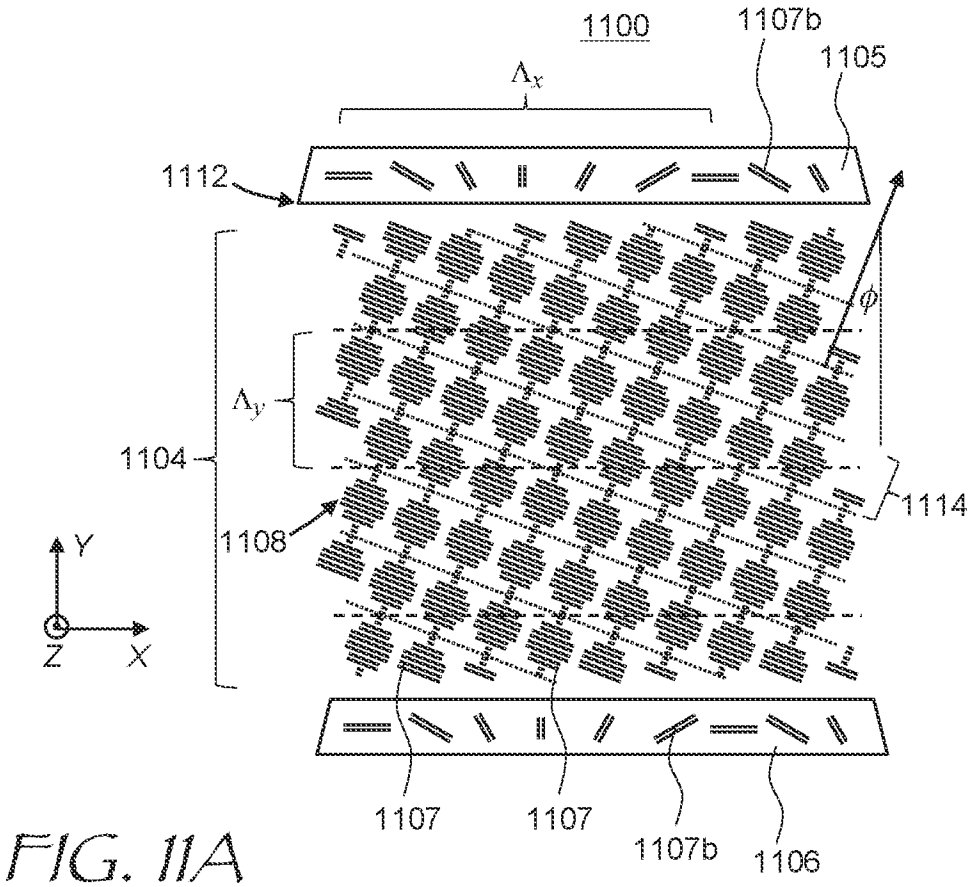


FIG. 11A

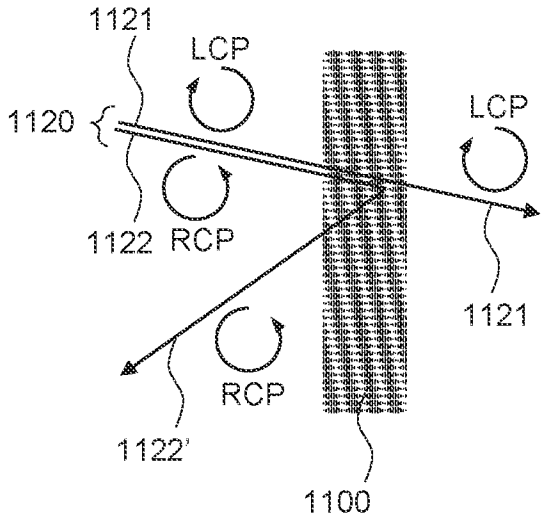


FIG. 11B

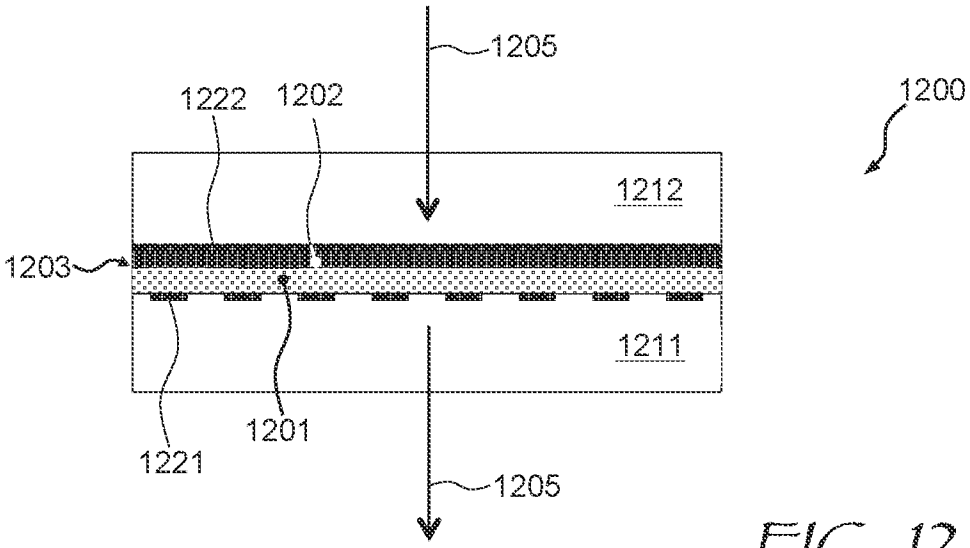


FIG. 12A

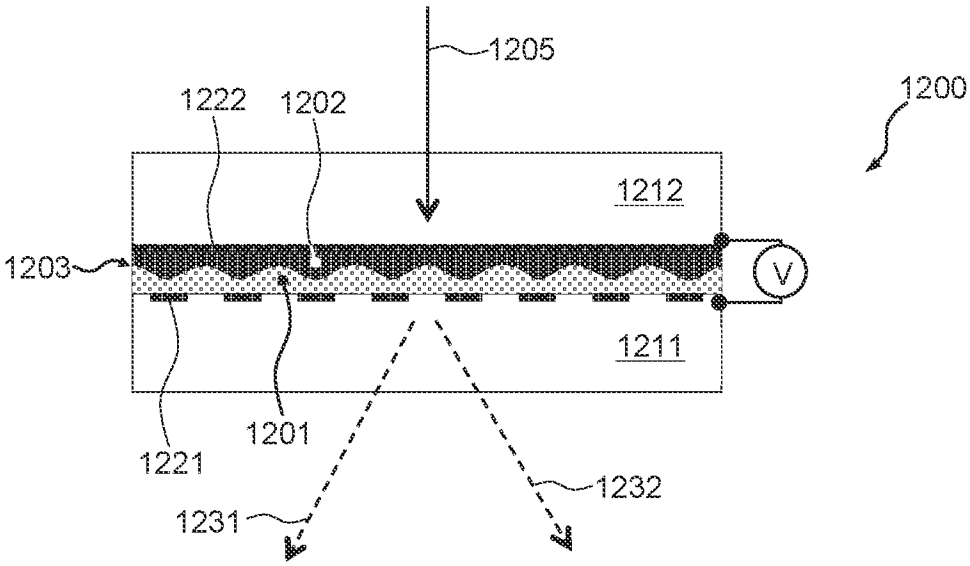


FIG. 12B

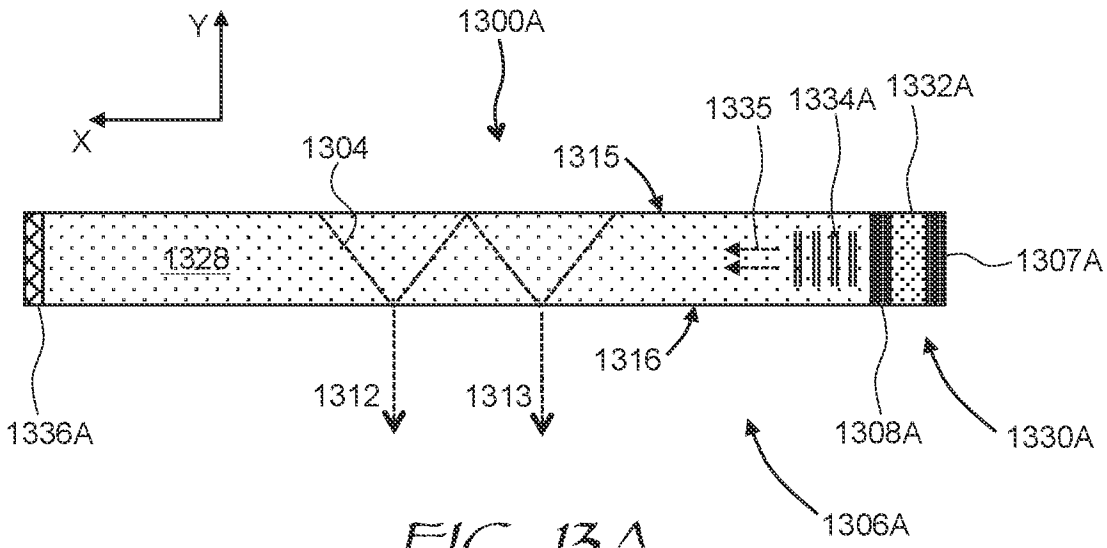


FIG. 13A

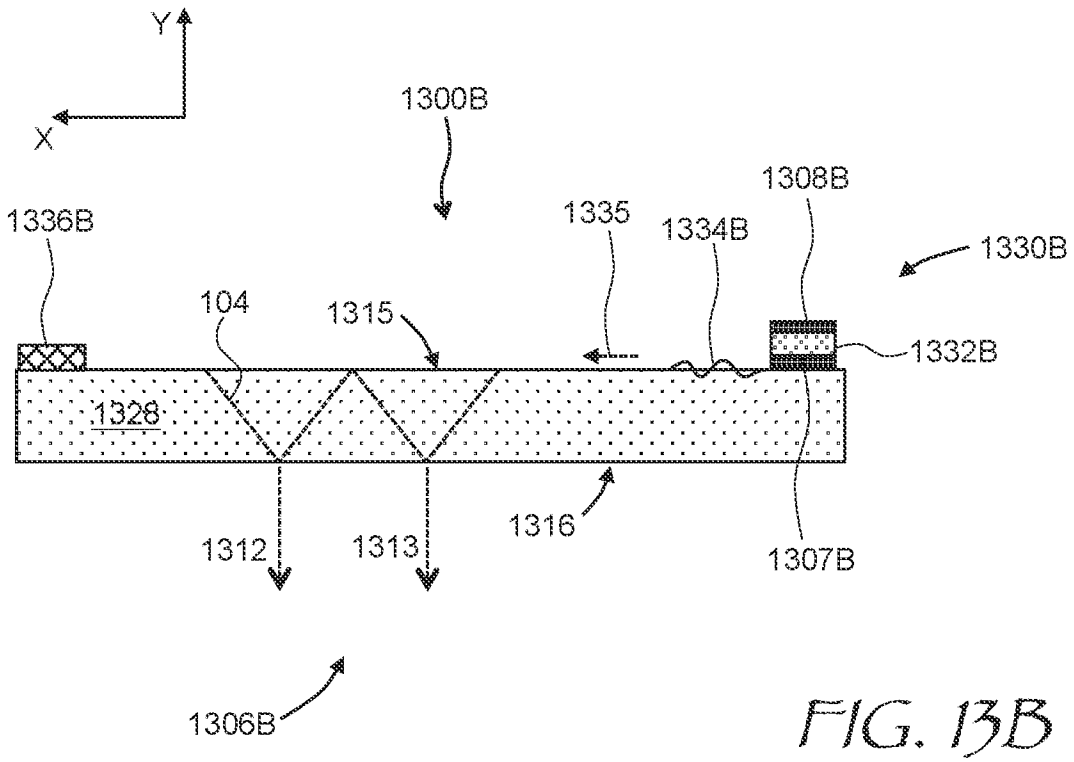


FIG. 13B

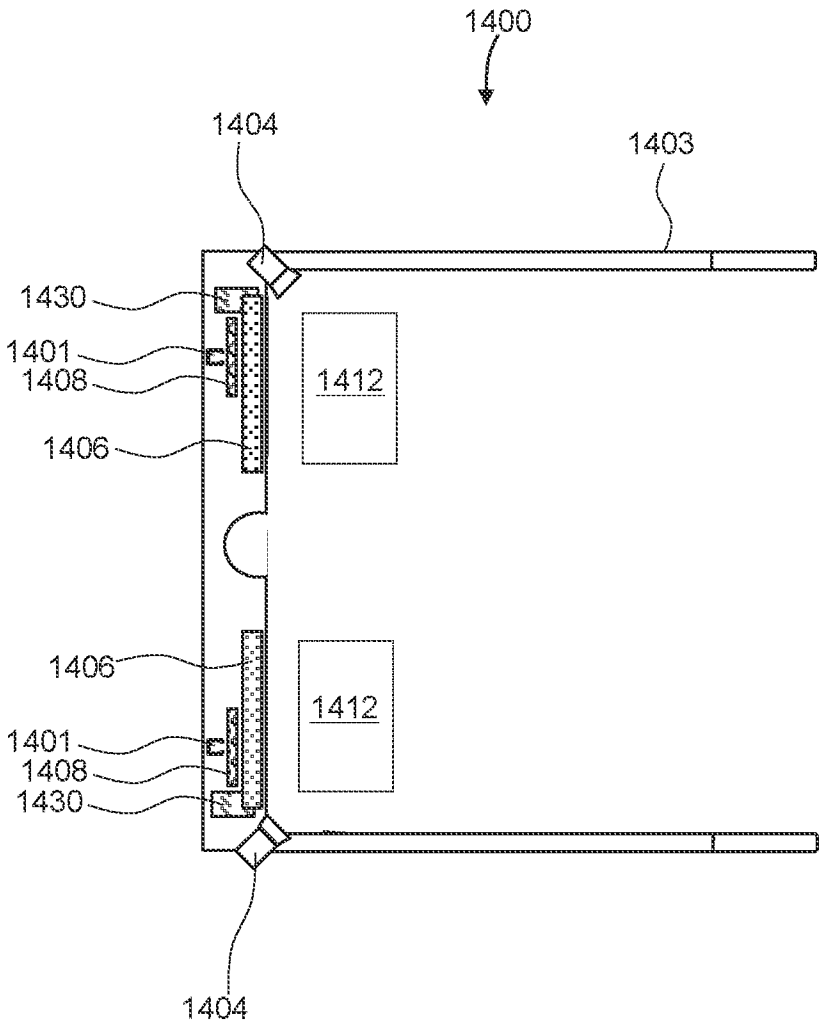
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FIG. 14

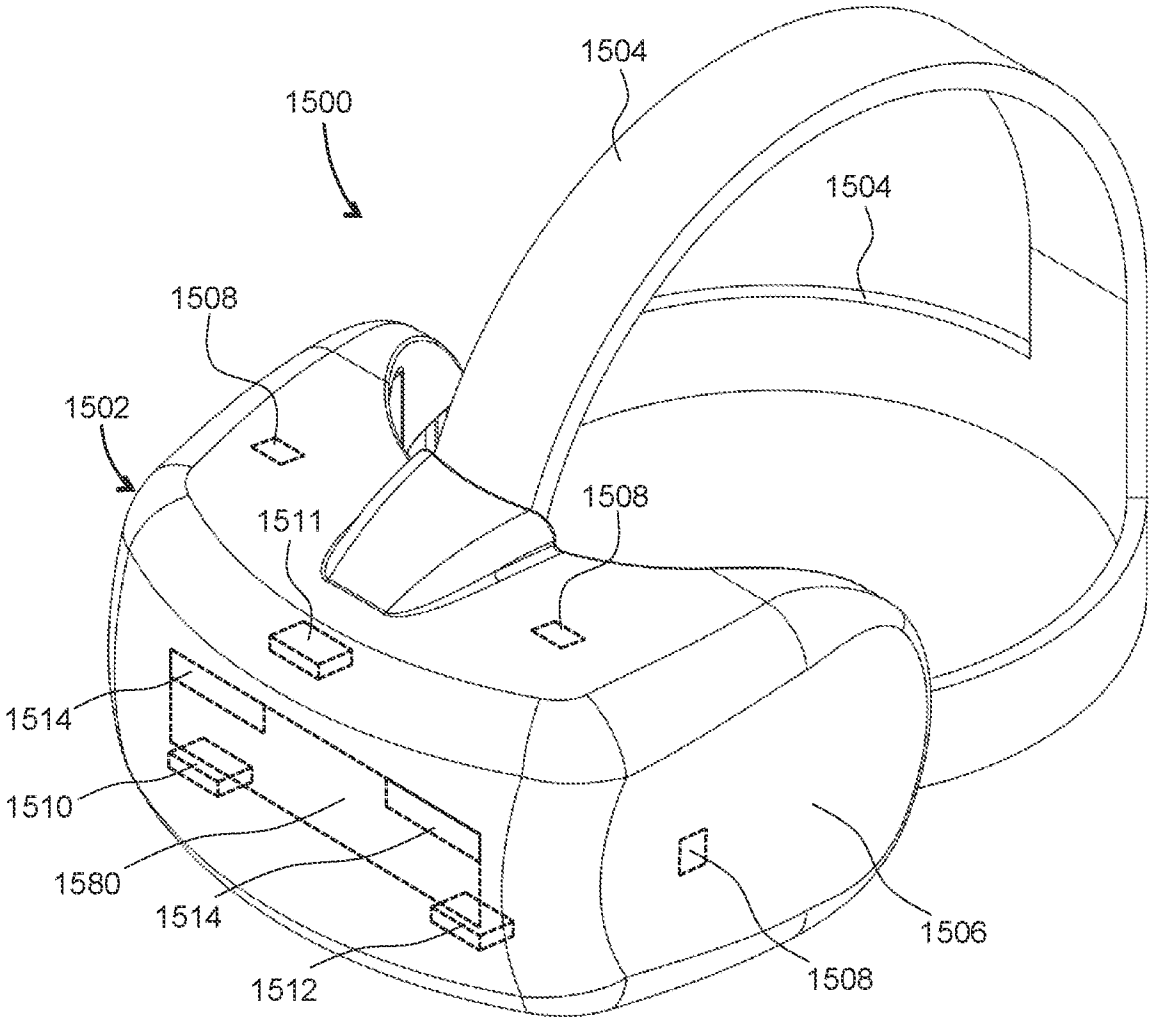
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FIG. 15

# INTERNATIONAL SEARCH REPORT

International application No
PCT/US2022/051801

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B27/01 G02B27/00 G02B5/18 G02B5/32
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)
G02B

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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| A | figures 11A-11C<br>paragraph [0194] - paragraph [0195]<br>paragraph [0197]<br>paragraph [0199]<br>paragraph [0054] | 1-13 |
| A | US 2016/085300 A1 (ROBBINS STEVEN [US] ET AL) 24 March 2016 (2016-03-24)<br>figure 2B<br>paragraph [0096] | 1-15 |
| A | US 2019/041634 A1 (POPOVICH MILAN MOMCILO [GB] ET AL) 7 February 2019 (2019-02-07)<br>figure 1A | 1-15 |

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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

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

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

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

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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 3 April 2023 | 13/04/2023 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Navarro Fructuoso, H |

1

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2022/051801

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