



(51) International Patent Classification:

G02F 1/017 (2006.01) G02B 27/10 (2006.01)
G02F 1/00 (2006.01) G02B 27/02 (2006.01)
G03H 1/04 (2006.01) G02B 27/18 (2006.01)
G02F 1/1362 (2006.01) G03H 1/02 (2006.01)
G02B 27/28 (2006.01)

(21) International Application Number:

PCT/US2024/044872

(22) International Filing Date:

30 August 2024 (30.08.2024)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

63/580,198 01 September 2023 (01.09.2023) US
63/602,074 22 November 2023 (22.11.2023) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM,

(54) Title: SYSTEMS AND METHODS FOR LIGHT MODULATION

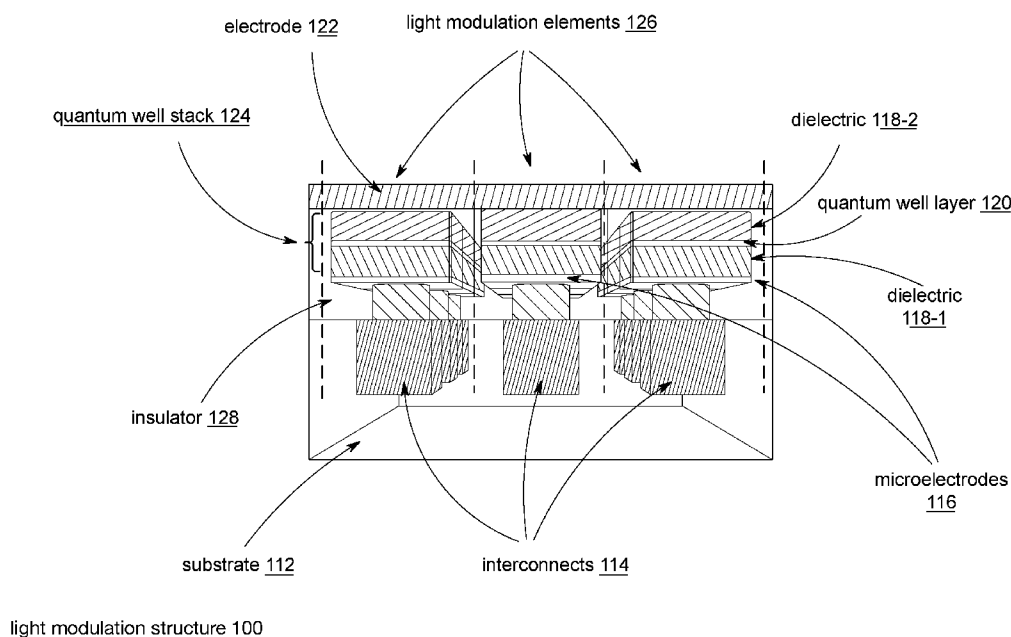


FIG. 2A

(57) Abstract: A device for modulating light includes a substrate with a plurality of electrical interconnects disposed on its top surface and an array of light modulating elements disposed above the substrate. A light modulating element of the device includes an array of light modulating elements includes a bottom electrode arranged on the substrate, with a bottom electrode coupled to an electrical interconnect of the plurality of electrical interconnects, the bottom surface of a first dielectric layer located over the bottom electrode and a quantum well layer overlaying the top surface of the first dielectric layer. A second dielectric layer is then disposed overlaying the top surface of the quantum well layer, with each light modulating element of the array of light modulating elements spatially separated from every other light modulating element of the array and a top electrode located atop the array of light modulating elements.

DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

- *with international search report (Art. 21(3))*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

SYSTEMS AND METHODS FOR LIGHT MODULATION**Inventors:**

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FIELD OF THE DISCLOSURE

[0001] The subject disclosure relates to three-dimensional (3D) optical display devices and associated applications for 3D projection and augmented/extended reality (AR).

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] Reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

[0003] FIG. 1A provides a cross section view of a light modulation structure in accordance with various aspects described herein;

[0004] FIG. 1B provides a perspective view of a light modulation structure in accordance with various aspects described herein;

[0005] FIGS. 2A and 2B provide perspective views of another light modulation structure in accordance with various aspects described herein;

[0006] FIG. 2C provides a perspective view of another light modulation structure in accordance with various aspects described herein;

[0007] FIG. 3 provides a cross section view of another light modulation structure in accordance with various aspects described herein;

[0008] FIGS. 4A and 4B provide perspective views of another light modulation structure in accordance with various aspects described herein;

[0009] FIG. 5A provides a cross section view of a light modulation element in accordance with various aspects described herein;

[0010] FIG. 5B provides a top-down view of an heater and conductive post structure for a light modulating element in accordance with various aspects described herein;

[0011] FIGS. 6A, 6B and 6C illustrate modulation responses for a multi-level light modulation structure in accordance with various aspects described herein;

[0012] FIG. 7 provides a schematic of a system for producing virtual 3D images, in accordance with various aspects described herein;

[0013] FIG. 8A provides an illustration of vergence and accommodation using natural vision, in accordance with various aspects described herein;

[0014] FIG. 8B provides an illustration of a 3D displayed image exhibiting a vergence-accommodation conflict, in accordance with various aspects described herein;

[0015] FIG. 9A provides a side view of a structure configured to overcome vergence and accommodation conflicts in a 3D optical display device, in accordance with various aspects described herein;

[0016] FIG. 9B provides another schematic of a system for producing virtual 3D images, in accordance with various aspects described herein;

[0017] FIG. 9C is a flowchart of a method for rendering and processing an image for 3D display, in accordance with various aspects described herein;

[0018] FIG. 10 provides an illustration of another example virtual reality (VR) system, in accordance with various aspects described herein;

[0019] FIG. 11 provides an illustration of another example virtual reality (VR) system, in accordance with various aspects described herein; and

[0020] FIG. 12 provides an illustration of another example virtual reality (VR) system.

DETAILED DESCRIPTION

[0021] One or more examples are now described with reference to the drawings, wherein like reference numerals are used to refer to like elements throughout. In the following description, for purposes of explanation, numerous details are set forth in order to provide a thorough understanding of the various examples. It is evident, however, that the various examples can be practiced without these details.

[0022] FIGS. 1A and 1B provide a cross-section and a perspective view, respectively, of a light modulation structure. In the example, light modulation structure 10 comprises a 4X4 array of conductive posts 16. In an example of implementation, substrate 12 can be an integrated circuit fabricated through front-end-of-line steps required for the formation of isolated CMOS elements. In a more specific example, an integrated circuit is fabricated to provide contact pads, such as interconnects 14 on which conductive posts 16 can be formed. In an alternative example, contact pads, such as interconnects 14, are formed on an integrated circuit as part of the formation of conductive posts 16. In the example, interconnects 14 are adapted to couple the integrated circuit to individual conductive posts of conductive posts 16. In a more specific example, interconnects 14 are formed by depositing one or more insulating materials, the one or more insulating materials comprising insulator 20, which can be configured to provide electrical isolation and/or thermal isolation between individual conductive posts of conductive posts 16. In an example of implementation and operation, insulator 20 comprises a plurality of insulating materials, configured to provide electrical isolation and/or thermal isolation between individual conductive posts of conductive posts 16. In a related example, the plurality of insulating materials, which make up insulator 20, are configured as a stack of layers.

[0023] In an example, insulator 20 can be patterned and etched to provide voids for the deposition of a conducting material for the formation of conductive posts 16. Example conducting materials can be one or more of aluminum, copper, tungsten, an alloy or any other reasonably efficient conducting material, but need not to comprise a metal material. In a specific example, a bottom electrode layer 24 can be deposited over the surface of insulator 20 and adapted for coupling to each of the conductive posts of conductive posts 16. In an alternative example, insulator 20 can be removed partially or in total after the formation of conductive posts 16 and replaced with a gas such as air or a vacuum used to provide electrical isolation and/or thermal isolation between individual conductive posts of conductive posts 16. In a specific example, each conductive post of conductive posts 16 can comprise a bottom and a top portion, where the bottom portion provides a connection between the conductive post and one or more interconnects of interconnects 14.

[0024] In an example of implementation, each of the conductive posts of conductive posts 16 can comprise conductive material exhibiting low resistivity. In a related example, the top portion of conductive posts 16 and interconnects 14 can be configured with conductive material exhibiting any of a relatively low or high resistivity. In an example of implementation and operation, conductive posts 16 can resemble the shape of vertical cylinders, with the conductive posts having a cylinder diameter a number of times smaller than a wavelength of light to be used with light modulation structure 10. In another related example, conductive posts 16 have a cylinder diameter in the range of 20 nm to 50 nm. In a related example, the cylinder diameter of conductive posts 16 is as small as could be provided by the most advanced semiconductor manufacturing processes, including lithography and etching processes. In an

alternative example, conductive posts 16 resemble the shape of vertical rectangular rods, where a cross section, taken parallel with the top surface of light modulation structure 10, has the shape of a rectangle. In a related example, conductive posts 16 resemble vertical rectangular rods with a rectangular cross section parallel to the top surface of light modulation structure 10, where the length of a diagonal of the rectangular cross section is multiples smaller than a wavelength of light to be used with light modulation structure 10. In a related example, the length of the diagonal of the rectangular cross section of conductive posts 16 is in the range of 20 nm to 50 nm. In a related example, the diagonal of the rectangular cross section of conductive posts 16 is as small as could be provided by the most advanced semiconductor manufacturing processes, including lithography and etching processes. In a related example, the light to be used with light modulation structure 10 is visible light, with the wavelengths of visible light ranging from approximately 380 nm to 750 nm. In an alternative example, ultraviolet (UV) or infrared (IR) light is used with light modulation structure 10.

[0025] In an example of implementation and operation, dielectric 18-1 can be formed over bottom electrode layer 24. In an alternative example, dielectric 18-1 can be formed over the array of conductive posts 16 for the formation of light modulation structure 10 without bottom electrode layer 24. In an example of implementation and operation, bottom electrode layer 24 is configured to exhibit low electrical resistivity and high optical reflectivity for the wavelengths used with light modulation structure 10. In a related example, bottom electrode layer 24 is configured to be optically opaque for wavelengths used with light modulation structure 10. In a related example, bottom electrode layer 24 comprises a stack of layers, where each of the layers can exhibit any of low electrical resistivity, high electrical resistivity and/or high optical reflectivity for wavelengths to be used with light modulation structure 10.

[0026] In an example of implementation and operation, bottom electrode layer 24 comprises (undoped) polysilicon. In an example of implementation, quantum well layer 20 is formed on the top surface of dielectric 18-1. In another example, dielectric 18-2 can then be formed over quantum well layer 20. In various examples herein, dielectrics, such as dielectric 18-1 and dielectric 18-2 can comprise insulating materials to electrically isolate quantum well layer 20 from other elements of light modulation structure 10. In an example, the choice of dielectric material for dielectric 18-1 and dielectric 18-2 can be based on various factors, such as electrical properties, and the manufacturing process for light modulation structure 10. Example dielectric materials can include, but are not limited to, Silicon Dioxide (SiO₂), Silicon Nitride (Si₃N₄), Aluminum Oxide (Al₂O₃), and Low-K Dielectrics, which include various organic and inorganic low-K materials, such as fluorinated silicon dioxide (SiOF), organosilicate glass (OSG), and porous low-K dielectrics. Other potential dielectric materials include High-K Dielectric materials that can be characterized as providing reduced physical thickness of a given dielectric layer, with examples including hafnium oxide (HfO₂), zirconium oxide (ZrO₂), and aluminum oxide (Al₂O₃). Other example dielectrics include organic polymers such as polyimides, Borophosphosilicate Glass (BPSG) and Spin-On Glass (SOG).

[0027] In a related example, quantum well layer 20 can be a thin layer sandwiched between barriers, such as dielectric 18-1 and dielectric 18-2, where the energy levels of the carriers (such as electrons and holes) in quantum well layer 20 are quantized in a direction perpendicular to quantum well layer 20. In an alternative example, quantum well layer 20 is a thin layer, on the order of a few nanometers to a few hundred nanometers thick, sandwiched between barriers, such as dielectric 18-1 and dielectric 18-2, with the barriers having a larger bandgap than quantum well layer 20. In an example, an electric field can be applied across a quantum well (stack), such as quantum well layer 20, inducing a change in (complex) index of refraction.

[0028] In an example, a dominant physical principle behind a change in (complex) index of refraction upon application of an electric field across a quantum well (stack) is the quantum confined Stark effect. In a related example, the quantum confined Stark effect induces mainly a change in the imaginary part of the (complex) index of

refraction. In another example, a dominant physical principle behind a change in (complex) index of refraction upon application of an electric field across a quantum well (stack) is the Franz–Keldysh effect. In a related example, the Franz-Keldysh effect induces mainly a change in the imaginary part of the (complex) index of refraction. In another example, a dominant physical principle behind a change in (complex) index of refraction upon application of an electric field across a quantum well (stack) is the Kerr effect. In a related example, the Kerr effect induces mainly a change in the real part of the (complex) index of refraction. In an example, by changing the electric field applied across a quantum well (stack) the (complex) index of refraction can be controlled and as such a quantum well (stack) can be used to modulate light, where the modulation can be any of amplitude, phase and/or polarization modulation.

[0029] In an example of implementation, an electrode material can be deposited on the top surface of dielectric 18-2 to form electrode 22. Example electrode materials for electrode 22 can be almost any efficient conductor that is reasonably transparent to light to be used with light modulation structure 10. A choice of electrode material for electrode 22 can be based on a variety of factors such as conductivity, transparency, manufacturability, and cost. In an example, electrode 22 can be configured in light modulation structure 10 to provide a common ground voltage for conductive posts 16.

[0030] In an example of operation, a voltage (relative to the common ground voltage provided by electrode 22) can be applied to each of the conductive posts of conductive posts 16, where the voltage applied to each of the conductive posts can be different from one conductive post to another conductive post. The voltage profile (relative to the common ground voltage provided by electrode 22) along bottom electrode layer 24 between two adjacent conductive posts of conductive posts 16 resembles a relatively linear interpolation between the voltages applied to each of the two adjacent conductive posts of conductive posts 16. Accordingly, the electric field across quantum well layer 20 resembles a linear interpolation profile along quantum well layer 20, enabling light modulation structure 10 to provide a (complex) reflectivity profile resembling a first order interpolation profile. In an example, the linear interpolation profile is in contrast to a light modulation structure comprising individual light modulation elements, as the (complex) reflectivity profile provided by a light modulation structure comprising individual light modulation elements resembles a zero order interpolation profile, due to each individual light modulation element having a relatively constant (complex) reflectivity profile along its top surface.

[0031] In an example of implementation and operation, a light modulation structure providing a (complex) reflectivity profile resembling a first order interpolation profile is preferred over a light modulation structure providing a (complex) reflectivity profile resembling a zero order interpolation profile. By changing the voltage (relative to the common ground voltage provided by electrode 22) at one or more conductive posts of conductive posts 16, the electric field across quantum well layer 20, resembling a linear interpolation profile along the quantum well layer 20, changes and as such the (complex) reflectivity profile changes, enabling dynamic modulation of light incident to the top surface of light modulation structure 10, where the modulation can be any of amplitude, phase and/or polarization modulation.

[0032] In more specific examples, light modulation properties, which may vary along light modulation structure 10, can be modified, enabling a display to generate dynamic, non-homogenous wavefronts from an incident light beam. In a related example, light modulation structure 10 can be configured as holographic display to display virtual three-dimensional (3D) content upon illuminating hologram patterns rendered on light modulation structure 100.

[0033] In an example, electrode 22 comprises one or more transparent electrodes. Specific example transparent electrodes can be configured from one or more of Indium Tin Oxide (ITO), Fluorine-Doped Tin Oxide (FTO), Graphene, Silver Nanowires, Carbon Nanotubes (CNTs), Conductive Polymers, Aluminum-Doped Zinc Oxide (AZO), Molybdenum-Doped Indium Oxide (IMO) or metal meshes of silver or copper wires. In various examples,

ITO is described as a thin film composed of indium oxide and tin oxide, while FTO is a tin oxide-based transparent conductor, the conductivity of which can be improved by doping with fluorine. In other examples, graphene can be a single layer of carbon atoms arranged in a hexagonal lattice, while CNTs can be described as single-walled or multi-walled carbon nanotubes adapted to create transparent conductive films.

[0034] In other examples, conductive polymers, such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), can be used as transparent conductive materials. In the example, AZO can be described as a transparent conducting oxide similar to ITO adapted to use aluminum instead of indium and IMO can be variously described as incorporating molybdenum into indium oxide. Finally, metal meshes comprise fine metal lines, such as silver or copper, that can be used as a transparent conductor.

[0035] In a specific example of operation, substrate 12, which may be a silicon substrate, includes control circuitry, which may comprise CMOS elements, for controlling an electric potential of electrode 22, along with the electric potential of each conductive post of conductive posts 16, such that the electric potential applied to electrode 22 and to each conductive post of conductive posts 16 can be controlled independently. In a specific related example, an electric field applied across a quantum well (stack) can evolve quasi-linearly along the quantum well (stack), resulting in a change in the optical properties along light modulation structure 10 that can be relatively smooth.

[0036] In another specific example, quantum well layer 20 can be configured to have a thickness between 1 nm and 30 nm, while dielectrics 18-1 and 18-2 can be configured to be thick enough to substantially prevent phenomena, such as, for example, dielectric breakdown and/or quantum tunneling, such as, for example, quantum tunneling between electrode 22 and quantum well layer 20 and/or quantum tunneling between bottom electrode layer 24 and quantum well layer 20. In a related example, quantum well layer 20 is configured to have a thickness between 1 nm and 5 nm. In an example implementation and operation, a quantum well, such as quantum well layer 20, may comprise any of Gold (Au), Platinum (Pt), Silver (Ag), Aluminum (Al), Silicon (Si), Germanium (Ge) and/or III-V semiconductor materials. In an example, dielectric 18-1 and dielectric 18-2 are configured to have a thickness between 1 nm and 30 nm. In an alternative example, dielectric 18-1 and dielectric 18-2 are configured to have a thickness between 1 nm and 10 nm. In an example of implementation, dielectric 18-2 can comprise a material different than the material comprising dielectric 18-1. In another example, dielectric 18-1 and dielectric 18-2 can comprise different materials, while each has a band gap larger than the band gap of the material comprising quantum well layer 20. In yet another example, quantum well layer 20 is replaced by a vertically stacked plurality of quantum well layers interposed with dielectric material.

[0037] In another example of implementation, conductive posts 16 are arranged in a square grid. In a related example, a pitch between two adjacent conductive posts in the array of conductive posts can be configured to be equal to or less than a wavelength of light to be used with light modulation structure 10. In an alternative example, a pitch between two adjacent conductive posts in the array of conductive posts can be configured to be equal to or less than half a wavelength of light to be used with light modulation structure 10.

[0038] In an alternative example of implementation, conductive posts 16 can be configured as a hexagonal grid configured in, for example, a honeycomb structure. In a related example, the smallest pitch in the hexagonal grid of conductive posts can be configured to be equal to or less than a wavelength of light to be used with light modulation structure 10. In an alternative example, the smallest pitch in the hexagonal grid of conductive posts can be configured to be equal to or less than half a wavelength of light to be used with light modulation structure 10. In an example, conductive posts 16 are configured in a staggered grid arrangement. In various additional examples, conductive posts 16 can be arranged in virtually any reasonable grid structure implementation. In an example, a layer, parallel to the top surface of light modulation structure 10 is adapted below bottom electrode layer 24, with the layer being

electrically isolated from conductive posts 16, where the layer has any of high optical reflectivity and/or optical opaque for wavelengths to be used with light modulation structure 10.

[0039] FIGs. 2A and 2B provide perspective views of another light modulation structure. In the example, light modulation structure 100 comprises a 3X3 array of light modulation elements 126. In an example of implementation, substrate 112 can be an integrated circuit fabricated through front-end-of-line steps required for the formation of isolated CMOS elements. In a more specific example, an integrated circuit is fabricated to provide contact pads, such as interconnects 114 on which light modulation elements 126 can be formed.

[0040] In an alternative example, contact pads, such as interconnects 114, are formed on an integrated circuit as part of the formation of light modulation elements 126. In the example, interconnects 114 are adapted to couple the integrated circuit to individual light modulation elements of light modulation elements 126. In a more specific example, interconnects 114 are formed by depositing one or more insulating materials, the one or more insulating materials may comprise insulator 128, which can be configured to provide electrical isolation and/or thermal isolation between individual elements of light modulation structure 100. In an example of implementation and operation, insulator 128 comprises a plurality of insulating materials, configured to provide electrical isolation and/or thermal isolation between individual elements of light modulation structure 100. In a related example, the plurality of insulating materials, which make up insulator 128, are configured as a stack of layers. In another specific example, light modulation elements 126 have a respective top and bottom, so that the top of some or all of light modulation elements 126 are coupled to a contact layer, such as electrode 122, while the bottom of each light modulation element of light modulation elements 126 is coupled through a microelectrode of microelectrodes 116 to one or more interconnects of interconnects 114 disposed on substrate 112.

[0041] In another specific example, light modulation elements 126 have a respective top and bottom, so that the top of some or all of light modulation elements 126 are coupled to a contact layer, such as electrode 122, while the bottom of each light modulation element of light modulation elements 126 is being coupled through a landing pad associated with a microelectrode of microelectrodes 116 to one or more interconnects of interconnects 114 disposed on substrate 112.

[0042] In an example, insulator 128 can be patterned and etched to provide voids for the deposition of a conducting material for the formation of microelectrodes 116. Example conducting materials can be one or more of aluminum, copper, tungsten, an alloy or any other reasonably efficient conducting material, but need not to comprise a metal material. In a related example, microelectrodes 116 comprise conducting material exhibiting low resistivity. In an alternative example, insulator 128 can be removed partially or in total after the formation of microelectrodes 116 and replaced with a gas such as air or a vacuum used to provide electrical isolation and/or thermal isolation between individual microelectrodes of microelectrodes 116. In a related example, microelectrodes 116 can be configured in a variety of sizes and shapes and in yet another example, the top of each microelectrode of microelectrodes 116 can be configured to provide a landing pad for an associated quantum well stack 124. In a specific example, each microelectrode of microelectrodes 116 can comprise a bottom and a top surface, where the bottom surface provides a connection between the microelectrode and one or more interconnects of interconnects 114. In a specific example, each microelectrode of microelectrodes 116 can comprise one or more of a conductive post and/or a landing pad, as well as intermediary layers between elements of the microelectrode. In an example, microelectrodes 116 are configured to provide high optical reflectivity for wavelengths used with light modulation structure 100. In a related example, microelectrodes 116 are configured to be optically opaque for wavelengths used with light modulation structure 100. In a related example, microelectrodes 116 comprise a stack of layers, where each of the layers can

exhibit any of low electrical resistivity, high electrical resistivity and/or high optical reflectivity for wavelengths to be used with light modulation structure 10.

[0043] In an alternative example, dielectric 118-1 can be formed over the top surface of microelectrodes 116, with quantum well layer 120 formed on the top surface of dielectric 118-1. In a related example, dielectric 118-2 can then be formed over quantum well layer 120, such that quantum well layer 120 is sandwiched between dielectric 118-1 and dielectric 118-2 to provide a quantum well “sandwich”. In an example, each of dielectric 118-1, quantum well layer 120 and dielectric 118-2 can be formed as layers that can subsequently be patterned and etched to provide trenches isolating a quantum well stack 124 of one light modulation element from the quantum well stack 124 of any other light modulation element of light modulation elements 126.

[0044] In a related example, trenches isolating a quantum well stack, such as quantum well stack 124, of one light modulation element from the quantum well stack of any other light modulation element of light modulation elements 126 can be filled with a material providing any of electrical isolation and/or thermal isolation. In a related example, light modulation structure 100 is configured to provide vacuum trenches between the quantum well stack, such as quantum well stack 124, of each of the light modulation elements of light modulation elements 126. In an alternative example, trenches isolating a quantum well stack, such as quantum well stack 124, of one light modulation element from the quantum well stack of any other light modulation element of light modulation elements 126 extend in the vertical direction to also provide isolation between individual microelectrodes of microelectrodes 116.

[0045] In various examples herein, dielectrics, such as dielectric 118-1 and dielectric 118-2 can comprise insulating materials to electrically isolate each quantum well layer, such as quantum well layer 120, from other elements of light modulation structure 100. In an example, the choice of dielectric material for dielectric 118-1 and dielectric 118-2 can be based on various factors, such as electrical properties, and the manufacturing process for light modulation structure 100. Example dielectric materials can include, but are not limited to, Silicon Dioxide (SiO₂), Silicon Nitride (Si₃N₄), Aluminum Oxide (Al₂O₃), and Low-K Dielectrics, which include various organic and inorganic low-K materials, such as fluorinated silicon dioxide (SiOF), organosilicate glass (OSG), and porous low-K dielectrics. Other potential dielectric materials include High-K Dielectric materials that can be characterized as providing reduced physical thickness of a given dielectric layer, with examples including hafnium oxide (HfO₂), zirconium oxide (ZrO₂), and aluminum oxide (Al₂O₃). Other example dielectrics include organic polymers such as polyimides, Borophosphosilicate Glass (BPSG) and Spin-On Glass (SOG).

[0046] In an alternative example, insulator 128 can be patterned and etched to provide voids, where each void is associated with a microelectrode of microelectrodes 116, for the deposition of quantum well stack 124. In an example of implementation, an electrode material can be deposited on the top surface of each of dielectric 118-2, where each dielectric 118-2 is associated with a light modulation element 126, to form electrode 122. Referring again to FIGS. 1A and 1B, example electrode materials for electrode 122 can be almost any sufficiently efficient conducting material that is reasonably transparent to light. A choice of electrode material for electrode 122 can be based on a variety of factors such as conductivity, transparency, manufacturability, and cost.

[0047] In a specific example of operation, substrate 112, which may be a silicon substrate, includes control circuitry, which may comprise CMOS elements, for controlling an electric potential of electrode 122, along with the electric potential of each microelectrode of microelectrodes 116, such that the electric potential applied to electrode 122 and to each microelectrode of microelectrodes 116 can be controlled independently. In a specific related example, the electric potential applied to electrode 122 and to each microelectrode of microelectrodes 116 determines the electric field applied across each quantum well stack, such as quantum well stack 124, where each quantum well stack is associated with a light modulation element of light modulation elements 126. In an example, an electric field can be

applied across a quantum well stack, such as quantum well stack 124, inducing a change in (complex) index of refraction. In an example, a dominant physical principle behind a change in (complex) index of refraction upon application of an electric field across a quantum well (stack) is the quantum confined Stark effect. In a related example, the quantum confined Stark effect induces a change in an imaginary part of the (complex) index of refraction. In another example, a dominant physical principle behind a change in (complex) index of refraction upon application of an electric field across a quantum well (stack) is the Franz–Keldysh effect. In a related example, the Franz-Keldysh effect induces mainly a change in the imaginary part of the (complex) index of refraction. In another example, a dominant physical principle behind a change in (complex) index of refraction upon application of an electric field across a quantum well (stack) is the Kerr effect.

[0048] In a related example, the Kerr effect induces mainly a change in the real part of the (complex) index of refraction. In an example, by independently controlling the electric field applied across each of the quantum well stacks, such as quantum well stack 124, of light modulation elements 126, the (complex) index of refraction of each light modulation element of light modulation elements 126 can be controlled independently and as such light modulation structure 100 can be used to modulate light, where the modulation can be any of amplitude, phase and/or polarization modulation. In another specific example, quantum well layer 120 of quantum well stack 124 can be configured to have a thickness between 1 nm and 30 nm, while dielectrics 118-1 and 118-2 can be configured to be thick enough to substantially prevent phenomena, such as, for example, dielectric breakdown and/or quantum tunneling, such as, for example, quantum tunneling between electrode 122 and quantum well layer 120 and/or quantum tunneling between a microelectrode of microelectrodes 116 and a quantum well layer, such as quantum well 120.

[0049] In yet another related example, quantum well layer 120 is configured to have a thickness between 1 nm and 5 nm. In an example implementation and operation, a quantum well, such as quantum well layer 120, may comprise any of Gold (Au), Platinum (Pt), Silver (Ag), Aluminum (Al), Silicon (Si), Germanium (Ge) and/or III-V semiconductor materials. In an example, dielectric 118-1 and dielectric 118-2 are configured to have a thickness between 1 nm and 30 nm. In an alternative example, dielectric 118-1 and dielectric 118-2 are configured to have a thickness between 1 nm and 10 nm. In an example of implementation, dielectric 118-2 can comprise a material different than the material comprising dielectric 118-1. In another example, dielectric 118-1 and dielectric 118-2 can comprise different materials, while each has a band gap larger than the band gap of the material comprising quantum well layer 120. In yet another example, one or more quantum well layers, such as quantum well layer 120, each associated with a light modulation element of light modulation elements 126, are each replaced by a plurality of layers, such that a resultant quantum well structure comprises a vertically stacked plurality of quantum well layers interposed with dielectric material.

[0050] In an example, an electric field applied between electrode 122 and each of microelectrodes 116 can be adapted to dynamically adjust diffractive interference patterns rendered using light modulation elements 126. In a specific example, the diffractive interference patterns rendered on light modulation structure 100 can be dynamically adapted to display dynamic three-dimensional (3D) content. In an example, light modulation structure 100 can be configured as holographic display for displaying virtual 3D objects and virtual 3D scenes based upon illuminating hologram patterns rendered on light modulation structure 100. In a related example, light modulation structure 100 is configured to be used with visible light, with the wavelengths of visible light ranging from approximately 380 nm to 750 nm. In an alternative example, light modulation structure 100 is configured to be used with ultraviolet (UV) or infrared (IR) light. In an example, a layer, parallel to the top surface of light modulation structure 100 is adapted in between or below microelectrodes 116, with the layer being electrically isolated from microelectrodes 116, where the

layer has any of high optical reflectivity and/or optical opaque for wavelengths to be used with light modulation structure 100. In a related example, the pixel pitch between two adjacent light modulation elements of light modulation elements 126 is equal to or smaller than a wavelength of light used with light modulation structure 100. In another example, the pixel pitch between two adjacent light modulation elements of light modulation elements 126 is equal to or smaller than half a wavelength of light used with light modulation structure 100.

[0051] FIG. 2C provides a perspective view of another light modulation structure. In an example referring to FIGS. 2A and 2B, isolation structure 168 can be formed between adjacent quantum well stacks, where the quantum well stacks may appear like quantum well stack 150, so that isolation structure 168 isolates one quantum well stack, such as quantum well stack 150, from any other quantum well stack of light modulation structure 110. In the example, light modulation structure 110 comprises a 3X3 array of light modulation elements 146. In an example of implementation, substrate 132 can be an integrated circuit incorporating contact pads, such as interconnects 134 on which light modulation elements 146 can be formed. In an alternative example, contact pads, such as interconnects 134, are formed on an integrated circuit as part of the formation of light modulation elements 146. In the example, interconnects 134 are adapted to couple the integrated circuit to individual light modulation elements of light modulation elements 146. In various examples, isolation structure 168 can comprise any of a conducting and/or a semiconductor material, wherein isolation structure 168 is enclosed by one or more insulating materials, such as insulator 138, such that isolation structure 168 is disposed between adjacent quantum well stacks, where the quantum well stacks may appear like quantum well stack 150.

[0052] In an example, isolation structure 168 can be formed with electrode 142, so that electrode 142 and isolation structure 168 are in electrical contact. In another example, isolation structure 168 can be formed separately from electrode 142, with electrode 142 and isolation structure 168 electrically coupled to each other. In an alternative example, isolation structure 168 can be formed separately from electrode 142, with an insulating material, such as insulator 138, electrically isolating isolation structure 168 from electrode 142. In an example where isolation structure 168 is electrically isolated from electrode 142, an electric potential can be applied to isolation structure 168, where the electric potential can be controlled independently from the electric potential applied to electrode 142 and to each microelectrode of microelectrodes 148. In an alternative example where isolation structure 168 is electrically isolated from electrode 142, no electric potential is applied to isolation structure 168. In another example, isolation structure 168 comprises a non-conducting material exhibiting any of electrical isolation and/or thermal isolation between individual quantum well stacks, where the quantum well stacks may appear like quantum well stack 150.

[0053] In an example, insulator 138 can be patterned and etched to provide voids for the deposition of a conducting material for the formation of microelectrodes 148. In a related example, microelectrodes 148 can be configured in a variety of sizes and shapes and in yet another example, the top of each of microelectrodes 148 can be configured to provide a landing pad for an associated quantum well stack 150.

[0054] In an example, a dielectric can be formed over the top surface of microelectrodes 148, with quantum well layer 140 formed on the top surface of the dielectric, with another dielectric formed over the top surface of quantum well layer 140, to provide a quantum well “sandwich”. In an example, the quantum well “sandwich” can be patterned and etched to provide trenches isolating one quantum well stack, such as quantum well stack 150, from any other quantum well stack, where each quantum well stack is associated with a light modulation element of light modulation element 146. In an example, the trenches isolating one quantum well stack, such as quantum well stack 150, from any other quantum well stack can be configured for formation of isolation structure 168 between each of the quantum well stacks 150, where the quantum well stacks may appear like quantum well stack 150.

[0055] In an alternative example, insulator 138 can be patterned and etched to provide voids, where each void is associated with a microelectrode of microelectrodes 148 for the deposition of a quantum well stack, such as quantum well stack 150. In an example of implementation, an electrode material can be deposited on the top surface of quantum well stacks, where the quantum well stacks may appear like quantum well stack 150, to form electrode 142. Referring again to FIGS. 1A and 1B, example electrode materials for electrode 142 can be almost any sufficiently efficient conductor that is reasonably transparent to light.

[0056] FIG. 3 provides a perspective view of another light modulation structure. In an example, microelectrodes 216 can be formed on a substrate, such as substrate 212, forming an array of microelectrodes 216. In an example of implementation, substrate 212, which may be a silicon substrate, can be an integrated circuit fabricated through front-end-of-line steps required for the formation of isolated CMOS elements. In a more specific example, an integrated circuit is fabricated to provide contact pads, such as interconnects 214 on which microelectrodes 216 can be formed. In an alternative example, contact pads, such as interconnects 214, are formed on an integrated circuit as part of the formation of an array of microelectrodes 216. In the example illustrated in FIG. 3, interconnects 214 are formed and adapted to couple the integrated circuit to individual microelectrodes 216. In a more specific example, interconnects 214 are formed by depositing one or more insulating materials, the one or more insulating materials comprising insulator 220, which can be configured to provide electrical isolation and/or thermal isolation between individual elements of light modulation structure 200.

[0057] In an example, the one or more insulating materials comprising insulator 220 can be patterned and etched to provide voids for the deposition of one or more conducting materials for the formation of microelectrodes 216. Example conducting materials can be one or more of aluminum, copper, tungsten, an alloy or any other reasonably efficient conducting material, but need not to comprise a metal material. In an alternative example of implementation, a plurality of voids provided in insulator 220 can be adapted for deposition of a first conducting material to form a bottom portion of microelectrodes, such as microelectrodes 216, followed by the addition of second conducting material, to form a top portion of microelectrodes, such as microelectrodes 216, where the top portion of each microelectrode is configured as a heater element, such as heater elements 218. In an example, the bottom portion of microelectrodes 219 comprises a conducting material with a low electrical resistivity and the top portion of microelectrodes 219, each top portion configured as a heater element, comprises a conducting material with a high electrical resistivity. In an alternative example, microelectrodes 219 do not comprise any portion configured as a heater element. In yet another example, each microelectrode of microelectrodes 219 solely comprises a portion configured as a heater element.

[0058] In a specific example, a heater element 218 can comprise a heater material. In an example, insulator 220 can be patterned and etched to provide voids for the deposition of heater material for the formation of heater elements, such as heater element 218, where each heater element is adapted for coupling to a bottom portion of microelectrodes 216. In an example, heater elements, such as heater element 218, can be formed on the surface of a bottom portion of microelectrodes 216. In another example, heater elements, such as heater element 218, can be manufactured separately and aligned with the bottom portion of microelectrodes 216. In another example, heater elements, such as heater element 218, can be manufactured separately and coupled directly to interconnects 214. In another example, heater elements, such as heater element 218, can be manufactured separately and aligned with voids in a previously patterned and etched insulator 220.

[0059] In an example, a heater element can be formed for each light modulating element to provide an array of microelectrodes 126, each microelectrode comprising a heater element, such as heater element 218. In an example, each microelectrode of microelectrodes 216 can be adapted to allow substantially independent application of current

to each heater element, such as heater element 218. Example heater materials include Tantalum Nitride (TaN) or any other material with suitable resistivity attributes. In an example, the stoichiometry of TaN (the ratio of Tantalum atoms to Nitrogen atoms) can be adjusted to achieve a desired electrical resistance for the heater elements, such as heater element 218, while optimizing current and voltage applied to each of the heater elements. In a related example, an additional factor defining the heater resistance is TaN film thickness. In the example, by varying TaN stoichiometry and film thickness the resistance of the heater can be adjusted in the range of 1 Ohm – 1000 Ohm.

[0060] In an example of implementation and operation, various materials can be applied over spatially separated microelectrodes, such as microelectrodes 216. In an example, a phase-change material (PCM), such as phase-change material 224, is applied over microelectrodes 216. In a related example, microelectrodes 216 are configured to be electrically coupled to phase-change material 224. In an example, phase-change material 224 can be any material having a reversible phase change property. In an example, phase-change material 224 can be adapted to be thermally interconverted between a crystalline phase and an amorphous phase on a relatively short time scale. In an alternative example, phase-change material 224 can be adapted to switch between one or more crystalline phases and one or more amorphous phases. In an example, switching from one phase of phase-change material 224 to another phase of phase-change material 224 can be achieved under a first thermal stimulus, whereas reverse switching can be achieved under a second thermal stimulus different from the first thermal stimulus.

[0061] In an example of implementation, each phase of phase-change material 224 exhibits a different (complex) index of refraction. In an example, the change in (complex) index of refraction obtained upon a change in phase of a phase-change material enables dynamic modulation of light incident to the phase-change material, where the modulation can be any of amplitude, phase and/or polarization modulation. In an example of implementation and operation, phase-change material 224 may comprise any of a chalcogenide phase-change material. Example phase-change materials include, but are not limited to GexSbyTez (Germanium Antimony Tellurium), Sb_xSy (Antimony Sulfide), Sb_xSe_y (Antimony Selenide) and Mo_xO_y (Molybdenum Oxide).

[0062] In various examples, phase-change material 224 can be deposited onto the array of microelectrodes 216 as a thin film, with each microelectrode being electrically isolated from any other microelectrode of microelectrodes 216. Deposition techniques for depositing a phase-change material can include, for example, Physical Vapor Deposition (PVD) with the phase-change material being evaporated from a solid source and then condensed onto the substrate. In another example, a phase-change material can be deposited using Chemical Vapor Deposition (CVD) with a chemical reaction of gaseous precursors used to form a thin film phase-change material on the surface of insulator 220 (and the exposed top surface of microelectrodes 216). In a related example, the top surface of insulator 220 can include one or more materials to provide mechanical, electrical or chemical protection for phase-change material 224. In a related example, the top surface of insulator 220 can include one or more materials configured as diffusion barrier(s) for phase-change material 224. In an example, phase-change material 224 can comprise a plurality of phase-change material layers adapted on top of each other, with each of the phase-change material layers comprising a different phase-change material and/or exhibiting a different stoichiometry.

[0063] In an example, an electrode material can be deposited on the top surface of phase-change material 224 to provide electrode 222. Example electrode materials for electrode 222 include almost any efficient conducting material that is reasonably transparent to light. A choice of electrode material for electrode 222 can be based on a variety of factors, such as conductivity, transparency, manufacturability, and/or cost. Specific example transparent electrode materials can be found above, with reference to FIG. 1A and 1B. In an example, electrode 222 can be configured in light modulation structure 200 to provide a common ground voltage for microelectrodes 216. In a specific example of implementation, one or more materials can be provided between phase-change material 224 and electrode 222

and/or over the top surface of electrode 222 to provide mechanical, electrical and/or chemical protection. In a related example, one or more materials can be provided between phase-change material 224 and electrode 222 configured as diffusion barrier(s) for phase-change material 224.

[0064] In a specific example of operation, substrate 212, which may be a silicon substrate, includes control circuitry, which may comprise CMOS elements, for controlling an electric potential of electrode 222, along with the electric potential of each microelectrode of microelectrodes 216, such that the electric potential applied to electrode 222 and to each microelectrode of microelectrodes 216 can be controlled independently. By applying a potential difference between a microelectrode of microelectrodes 219 and electrode 222, current will flow between the microelectrode and electrode 222 through phase-change material 224. The flow of current through phase-change material 224 enables a change in phase in a portion of phase-change material 224, with the shape and size of the portion defined by the current flow through phase-change material 224. In the example where microelectrodes 219 comprise a heater element, current will also flow through the heater element, upon which heat is generated enabling a faster transition from one phase to another phase within a portion of phase-change material 224. In an example, the current pulse profile of the current that flows between a microelectrode of microelectrodes 219 and electrode 222, together with the associated heat pulse profile (for the case where the microelectrode comprises a heater element, such as heater element 218) determines which phase is switched to.

[0065] In an example, current driven between a microelectrode of microelectrodes 216 and electrode 222 can be provided as a current pulse of programmable amplitude and duration. In a specific example, the various attributes of a current pulse driven between a microelectrode of microelectrodes 216 and electrode 222 for a time period T, such as, for example, attack, decay, sustain and release, can be dynamically modified to change the light modulating effects for light modulation structure 200. In a related example, pulse attributes can be arbitrarily modified to generate current pulses with various shapes. In a related example, the amount of current driven between a microelectrode of microelectrodes 216 and electrode 222 can be determined based on an amount of heat required to enable a phase transition as different phase transitions require different amounts of heat. In a specific example, a transition from amorphous phase to crystalline phase can be gradual, requiring a lower heat profile over a relatively longer period of time, while a transition from crystalline phase to amorphous phase can happen relatively quickly, thereby requiring a higher heat profile for a relatively short period of time. In some examples, for a transition from a particular crystalline phase to a particular amorphous phase, the portion of phase-change material 224 transitioned from crystalline phase to amorphous phase can include useful intermediate stages, with each stage associated with a different shape and/or size of the transitioned portion, discussed further with reference FIGS. 6A thru 6C.

[0066] In an alternative example, insulator 220 can be removed partially or in total after the formation of microelectrodes 216 and replaced with a gas such as air or a vacuum used to provide electrical isolation and/or thermal isolation between the individual microelectrodes of microelectrodes 216 of light modulation structure 200.

[0067] In another example of implementation, light modulation structure 200 can include additional material structures to provide additional functionality. In a related example, a material layer exhibiting high optical reflectivity, configured as mirror, is adapted below phase-change material 224, where the material layer is electrically isolated from microelectrodes 216, in order to reflect light incident to the top surface of light modulation structure 200. In a related example, a set of micro-mirror is adapted below phase-change material 224, with each micro-mirror being electrically isolated from microelectrodes 216, in order to reflect light incident to the top surface of light modulation structure 200. In another related example, an opaque layer can be adapted below phase-change material 224 to shield elements underneath phase-change material 224, such as, for example, CMOS elements, from incident light. In another example, a set of light shielding structures can be adapted below phase-change material 224. In a related

example, a single light shielding structure or a set of light shielding structures may be configured to reflect incident light. In another example, one or more light shielding structures can be configured as one or more meta-surfaces to block specific wavelengths and/or wavelength ranges of light.

[0068] In an example, the pitch between two adjacent microelectrodes of microelectrodes 216 is equal to or smaller than a wavelength of light used with light modulation structure 200. In a related example, the pitch between two adjacent microelectrodes of microelectrodes 216 can be configured to be equal to or less than half a wavelength of light used with light modulation structure 200. In yet another example, the distance between each of microelectrodes 216 can be adapted to vary across an array of microelectrodes 216. In an example, microelectrodes 216 can be configured in any arrangement, including a square grid arrangement, a hexagonal grid arrangement or a staggered grid arrangement.

[0069] FIGs. 4A and 4B provide perspective views of another light modulation structure. In the example, light modulation elements 246 include interconnects 234, heater elements 238 and electrodes 236 for coupling interconnects 234 to heater elements 238. In an example, voids can be provided within heater elements 238 associated with each light modulation element to, for example, manage the flow of heat between adjacent light modulation elements 246. In an example, voids can be configured to reduce thermal crosstalk between adjacent light modulation elements 246 and/or prevent unintentional phase change of the phase change material in a light modulation element heated by a light modulation element of light modulation elements 246. In a related example, voids can be adapted to reduce overall thermal energy and electrical current requirements for heating the cell above a given phase change threshold temperature. In practice, reduced energy consumption can be an important product feature, especially when a 3D projection device is utilized in a battery powered device.

[0070] In the examples of Figures 4A and 4B, light modulating elements 246 can include phase-change material 244 configured as a layer on top of isolated heater elements 238. In a related example, the surface of phase-change material 244 can include one or more materials comprising protective layer 248 to provide mechanical, electrical or chemical protection for phase-change material 244.

[0071] FIG. 5A provides a cross section view of an example light modulation structure. In the example, a microelectrode, such as microelectrodes 116 referring to FIG. 2A, comprise a conductive bottom portion 402, coupled at one end to one or more interconnects, such as interconnects 214 provided at the top surface of a substrate, such as substrate 212 referring to FIG. 3. At another end, conductive bottom portion 402 is coupled to a heater element 404. In an example, heater element 404 is configured to provide heat to phase-change material 408 in response to current flowing between heater element 404 and electrode 410. In an example, micro-mirror 406 is formed over heater element 404. In an alternative example, heater element 404 and micro-mirror 406 are a same material adapted for high resistivity and relatively high reflectivity.

[0072] FIG. 5B provides a top-down view of an example light modulation structure, illustrating the top surface of the micro-mirror and heater elements.

[0073] FIGS. 6A, 6B and 6C illustrate a multi-level light modulation structure with reference to FIG. 3. In each of FIGS. 6A, 6B and 6C, a transition response for a modulation level of a 4-level light modulation structure is shown, where each transition response is associated with a heater current applied to heater elements. In an example referring to FIG. 3, starting with a solid crystalline phase, when a relatively lower level of heat is applied by heater elements 218, a small localized transition response is induced as the crystalline phase of the associated phase-change material transitions to an amorphous phase at each heater element, as illustrated in FIG. 6A. Increasing the relative level of heat applied by each heater element of heater elements 218 can result in a larger relative localized transition response

to an amorphous phase, as illustrated in FIG. 6B. FIG. 6C illustrates an even larger transition response from an even higher level of heat applied. Accordingly, referring again to the example of FIG. 3, light modulation elements 226 can be configured to provide 4-level modulation (as well as an almost infinite number of transition response levels), enabling multi-level modulation of light from a given incident light source.

[0074] Referring to FIG. 4A, in another example of implementation, two or more light modulation elements of light modulation elements 226 can be configured to share a phase-change material, such as phase-change material 244, separated from the phase change material shared by any other light modulation elements of light modulation elements 244.

[0075] In an example, any of the light modulation structures disclosed herein can be implemented with an illumination source, with the illumination source providing illumination to the top surface of the light modulation structure. In an example, the light modulation structures as disclosed herein are configured to modulate the illumination incident to the top surface of the light modulation structure, as provided by an illumination source, where the modulation can be any of amplitude, phase and/or polarization modulation. In a related example, light modulation structures as disclosed herein are configured to be used with visible light, with the wavelengths of visible light ranging from approximately 380 nm to 750 nm. In an alternative example, light modulation structures as disclosed herein are configured to be used with ultraviolet (UV) or infrared (IR) light. **FIG. 7** provides a schematic diagram of an example 3D display system for displaying virtual content in accordance with various aspects described herein. In an example, virtual content comprises two dimensional (2D) images, three dimensional (3D) objects and/or three dimensional (3D) scenes. In an example, 3D display systems can be adapted, by adding eye tracking and/or programmable optics, to provide more natural coordination between vergence and accommodation, thereby reducing the conflict and associated discomfort. In a particular example, a 3D display system can be adapted, by adding varifocal lenses to dynamically adjust a focal plane to match an associated perceived depth, thereby enabling vergence and accommodation to function more naturally for a person using the 3D display system.

[0076] In an example, augmented reality (AR) and virtual reality (VR) display systems can be adapted with active optics. Active optics in augmented reality (AR) and virtual reality (VR) display systems can refer generally to the use of dynamically adjustable optical elements, such as opto-electronic elements, opto-mechanical elements and systems to enhance the quality and performance of AR and VR display systems. Active optics can be utilized to optimize various aspects of the optical system of augmented reality (AR) and virtual reality (VR) display systems in real-time, improving the user experience, comfort, and realism of augmented reality (AR) and virtual reality (VR) content. In an example, an augmented reality (AR) display system can be adapted to overlay virtual content directly on a real-world view.

[0077] In a related example, a virtual reality (VR) system tries to mimic the experience of having virtual objects overlaid on a real-world view by incorporating one or more cameras that capture a real-world view, where the camera captured real-world view is displayed on one or more displays of the virtual reality (VR) system for perception by the user; virtual content can be overlaid on the camera captured real-world view before being displayed to the user. In an example of implementation and operation, active optics can be used in augmented reality (AR) and virtual reality (VR) systems to dynamically adjust the focus of virtual content. In an example, dynamically adjusting the focus of virtual content can be used in an augmented reality system to accommodate and/or match the distance of the virtual content with the distance of the real-world objects being observed. In the example, both virtual and real objects can appear substantially sharp and in focus for a user simultaneously. In a related example, dynamically adjusting the focus of virtual content can contribute to a more seamless and immersive AR and/or VR experience.

[0078] **FIG. 8A** provides an illustration of vergence and accommodation in natural vision. As illustrated, in normal binocular vision vergence and accommodation cooperate to place a sharp image of a given object on the fovea of each eye of a viewer. In the example of FIG. 8A, vergence can be referred to as the process by which a viewer's eyes converge or diverge to focus on an object at a specific depth. In an example, when an object is closer to a viewer, their eyes converge (turn inward), and when an object is farther away, their eyes diverge (turn outward). In various examples, convergence and/or divergence allows one's brain to process disparity between images received from each eye to perceive at least an approximation of depth. Accommodation can refer to an adjustment of the focusing lens (lens) inside one's eyes to enable focusing on objects at different distances.

[0079] In an explanatory example, when one "looks" at a nearby object, the lens becomes thicker to enable focusing the object image on the retina. In a contrasting example, when one looks at a distant object, this lens becomes thinner. In a further example, in natural viewing conditions, vergence and accommodation are tightly linked, so that when one looks at an object, their eyes converge to that point, and the lenses in each eye adjust their shape to focus on that distance. In an example, this coordinated process can help the brain to accurately perceive depth and distance of objects in a given setting.

[0080] As mentioned with reference to FIG. 8B below, a vergence-accommodation conflict can be problematic in stereoscopic 3D display systems. In an example of implementation and operation, active optics can be employed to create a dynamic focal plane that adjusts according to the perceived depth of the virtual objects. This reduces the discomfort and visual fatigue caused by the conflict between eye convergence (vergence) and the fixed distance to the flat surface (accommodation). In another example of implementation, active optics can enable the expansion of the effective field of view by adjusting the optical system to direct the virtual content to a wider area of the user's visual field. In another example, active optics can track the user's eye movements and adjust the displayed virtual content accordingly. In an example, by knowing where a user is looking, the VR/AR system can attempt to ensure that the virtual content of interest is always in focus and properly aligned. In a related example, active optics can adjust the amount and direction of light entering the user's eyes, enhancing the visibility of virtual content in different lighting conditions. This can involve controlling the intensity, polarization, and direction of light to improve contrast, reduce glare, and create more realistic visual effects.

[0081] In the example of FIG. 1, virtual reality system 10 can be configured to enable dynamically adjustable optical elements. As illustrated, virtual reality system 10 can be configured to provide left and right face tracking information and left and right eye tracking information for a user. In an example, tracking information can be used with each of the left and right lenses to focus the respective lenses for displayed content.

[0082] **FIG. 8B** provides an illustration of a stereoscopic 3D display system to display three dimensional (3D) objects and/or three dimensional (3D) scenes exhibiting a vergence-accommodation conflict. Stereoscopic 3D display systems, with images presented to each eye being slightly shifted relative to each other in order to create a perception of depth, can exhibit a phenomenon, sometimes referred to as "vergence-accommodation conflict". In an example relevant to stereoscopic 3D display systems, a "conflict" exhibits, because images presented to each eye are typically displayed on a flat surface, creating a fixed focal plane. In an example, the accommodation process can be fixed at the flat surface, regardless of a perceived depth of associated three dimensional (3D) objects.

[0083] In an example of operation, the disparity between the vergence (convergence/divergence), imposed by the disparity in the images presented to each eye, and the accommodation fixed to the distance of the flat surface can lead to a vergence-accommodation conflict. In various examples, a vergence-accommodation conflict can result in discomfort, visual fatigue and nausea. In an example, a vergence-accommodation conflict can lead to a reduction in depth perception of displayed three dimensional (3D) objects and/or three dimensional (3D) scenes after longer use

of a stereoscopic 3D display system. For example, when one's eyes attempt to converge or diverge to match a perceived depth of displayed three dimensional (3D) objects, the accommodation can remain fixed, thereby straining one's eye muscles and causing visual discomfort. In an example, this discomfort can be referred to as "vergence-accommodation conflict discomfort".

[0084] FIG. 9A provides an illustration of an example virtual reality (VR) system 500 that reduces or even eliminates vergence-accommodation conflict. Referring again to FIG. 7, active optics can be adapted to a three-dimensional (3D) display system, such as, for example, a virtual reality headset, to dynamically adjust a focal plane to match an associated perceived depth. In the example of FIG. 7, virtual reality system 10 incorporates, among other elements, eye tracking to actively measure a position and movements of a user's eyes, requiring complex hardware and/or software components that increase cost, power consumption, latency and computation requirements.

[0085] In a related example, 3D renderings as displayed by a 3D display system, such as a virtual reality headset, can appear unnatural or otherwise can comprise undesired artifacts. For example, when a real object is observed in a natural setting, the eye identifies and focuses on a dominant object in the foreground, with the background being blurred because it is out of focus. In systems using active optics, a 3D rendering as displayed by a 3D display system can result in both the foreground object(s) and the background being in focus, which does not happen in the real world. Moreover, even using active optics, the eyes are limited in their ability to converge from a far field to a near field object.

[0086] In the example of FIG. 9A, a virtual reality (VR) system can include a 2D stereoscopic display 504, along with one or more holographic displays, such as HXR display 510. In an example of implementation and operation, the one or more holographic displays can be implemented using one or more spatial light modulators. In an example, the one or more holographic displays are configured as 3D displays adapted to diffract incident light to display 3D content directly viewable without the need of special optics or special glasses. In an example, a 2D stereoscopic display provides a single plane of focus.

[0087] In another example referring to FIG. 9A, a 2D stereoscopic display 504 and one or more holographic displays 510 are combined, in order to reduce or fully eliminate some or all of the deficiencies of 3D display systems suffering from vergence-accommodation conflict and that employ active optics to dynamically adjust a focal plane to mitigate vergence-accommodation conflict. In an example of implementation, 2D stereoscopic display 504 can be configured in front of the eyes of a user. In a related example of implementation, a 2D stereoscopic display system can be implemented by one 2D display or by two 2D displays, one for each eye. In another related example, a 2D stereoscopic display system can be implemented by a plurality of 2D displays 504.

[0088] Example display technologies for a 2D stereoscopic display include virtually any type of display technology (e.g. micro-led display technology, OLED display technology, LCD display technology LCoS display technology, or another type of spatial light modulator technology, etc). In an example of operation, a 2D stereoscopic display can be adapted to render 3D objects and 3D scenes in the 'far' field (beyond a distance of ~1.5-2m), such as rendering a background scene. Other examples include using a 2D stereoscopic display to render 3D objects or 3D scenes in the 'near' field / foreground (at a distance of ~1.5-2m or less).

[0089] In an example of implementation, in addition to a 2D stereoscopic display, an AR or VR display system can include one or more holographic displays per eye, or alternatively, a single holographic display for both eyes. In the example, the holographic display(s) can be used in a mode to render 3D objects and 3D scenes in the 'near' field and/or in the foveated area. In a related example, one or more holographic displays are used to render 3D objects close to the user (3D objects in the 'near' field / foreground), while a 2D stereoscopic display is used to render 3D objects and 3D scenery farther away of the user (3D objects and 3D scenery in the 'far' field / background). In yet

another related example, the virtual reality (VR) system arrangement of FIG. 9A employs one or more holographic displays for displaying 3D renderings with high resolution and a lot of detail in the foveated area, where a 2D stereoscopic display is employed for rendering everything around the foveated area.

[0090] In another related example referring to FIG. 9A, eye tracking can be adapted for use in a virtual reality (VR) system in order to determine the foveated area for a given user of the virtual reality (VR) system arrangement. In an example, the resolution, and/or amount of detail, can vary across what is displayed by the virtual reality (VR) system arrangement of FIG. 9A according to one or more “fixation points”. In the example, a fixation point can be the highest resolution region of what is displayed and corresponds to the foveated area for a user. In another example of implementation and operation, an illumination source can be provided for each holographic display to illuminate the holographic display. In a related example, a single holographic display would require a single illumination source. In an alternative example, a plurality of illumination sources is provided for a single holographic display, where each illumination source provides visible light with a different wavelength. In an example of operation, holographic displays can be adapted to interact with incident light from the illumination sources to generate static and/or dynamic non-homogenous wavefronts, enabling a user to observe virtual content, including two dimensional (2D) images, virtual 3D objects and virtual 3D scenes.

[0091] In an example, spatial light modulators can be used as holographic displays for displaying virtual content, including 2D images, 3D objects and 3D scenes in the ‘near’ field (distance of $\sim 1.5\text{-}2\text{m}$ or less), effectively solving the vergence-accommodation conflict without requiring bulky and costly active optics and compute-intensive eye-tracking, resulting in cheaper, more compact and lighter VR and/or AR headsets. Moreover, making use of 2D stereoscopic displays to render 3D objects and 3D scenes in the ‘far’ field instead of holographic displays greatly reduces compute requirements on the holographic displays. In a related example, 2D stereoscopic displays are much less compute intensive compared to holographic displays.

[0092] In an example of implementation and operation, by displaying virtual content in the “near” field only with one or more holographic displays, vergence-accommodation conflict is reduced or even eliminated, because holographic displays mimic all visual cues as a real object would generate them. In addition, by using a 2D stereoscopic display for rendering virtual content in the “far” field, the compute requirements imposed on the one or more holographic displays is relaxed. In an example, a virtual reality (VR) headset can be configured with an optical subsystem. In an example of implementation and operation, an optical subsystem can be adapted to (re)direct, filter and/or magnify/demagnify wavefronts generated by one or more spatial light modulators and combine generated wavefronts with graphical content provided on a 2D stereoscopic display.

[0093] In another example of implementation, an example virtual reality (VR) system arrangement, such as the virtual reality (VR) system arrangement of FIG. 3A, can be implemented with at least one of one or more compute elements, such as, for example, one or more holographic processors, a control management subsystem, memory, a power management subsystem, one or more embedded batteries, and/or one or more connectors configured for connecting to one or more external batteries.

[0094] In various examples, compute elements, such as, for example, one or more holographic processors execute(s) Computer Generated Holography (CGH) algorithms. In an example, the Computer Generated Holography (CGH) algorithms can compute light interference patterns. In an example, the light interference patterns can be used to determine the programming of light modulating elements (corresponding to optical pixels) of one or more spatial light modulators, such as the spatial light modulators configured as holographic displays in the virtual reality (VR) system arrangement of FIG. 9A, in order for the one or more spatial light modulators to generate desired wavefronts. In an example, CGH algorithms, which can comprise nonlinear, nonconvex, and multidimensional inverse problems

can be used to compute hologram patterns for rendering on one or more holographic displays, such as the holographic displays of the virtual reality (VR) display system arrangement of FIG. 9A. Computer Generated Holography (CGH) algorithms can be based on one or more of a Fresnel Transform-Based model, an Angular Spectrum model, a Point Source method, a Gerchberg-Saxton Algorithm, an Iterative Fourier Transform Algorithm (IFTA) and/or a Wavefront Propagation algorithm (such as, for example, wavelet transform, wavefront recording and reconstruction and kinoform).

[0095] Additional related methods can include using random-phase encoding/decoding techniques to represent complex scenes and/or deep learning techniques, such as convolutional neural networks. In an example of implementation and operation, the one or more compute elements, such as, for example, holographic processors, can be fully embedded in the virtual reality (VR) system arrangement. In another example, one or more of the one or more compute elements, such as, for example, holographic processors, may be external to the virtual reality (VR) system arrangement. In a related example, data, such as, for example, hologram patterns can be transmitted from the one or more compute elements external to the virtual reality (VR) system arrangement over a cable and/or a wireless link to the virtual reality (VR) system arrangement.

[0096] In an example of implementation and operation, a control management subsystem can be adapted to receive and transmit digital data and/or to control subsystems and components for optimal interaction between each of the subsystems and components of the virtual reality (VR) system arrangement. In another example of implementation and operation, a VR and/or AR display system can be configured with one or more spatial light modulators used as holographic displays. In related examples, a system can be configured with one or multiple spatial light modulators per eye, or one single spatial light modulator for both eyes. In an example, spatial light modulators can be configured to be located in front of a user's eyes, but they may also be configured in the VR and/or AR system offset from the front of the user's eyes. In other examples, a VR and/or AR display system can be configured with one or more illumination sources (e.g. one or more laser sources with coherent light) and in a related example, a VR and/or AR display system can be configured with an optical subsystem associated with each spatial light modulator.

[0097] In an example of operation, an illumination source can be adapted to provide illumination for the spatial light modulator. In another example, an optical subsystem (or subsystems) can be provided between the spatial light modulator and the user's eye. In yet other examples, one or more optical subsystems can be implemented with optics adapted to (re)direct, filter and/or magnify/demagnify wavefronts generated by a spatial light modulator. In a related example, wavefronts enabled by the optical subsystem can be captured by the user's eye as virtual content, including two dimensional (2D) images, three dimensional (3D) objects and/or three dimensional (3D) scenes. In an example, the field of view of a VR and/or AR system can be determined by the pixel pitch of a given spatial light modulator, along with the magnification factor associated with one or more optical subsystems. In various examples, 3D objects and 3D scenes in a VR and/or AR display system are generated using digital holography, enabling that a user's perception will be based on natural visual cues.

[0098] In various examples, digital holography can be compute intensive. Accordingly, referring again to FIG. 9A and 9B, a 2D stereoscopic display can be adapted to provide a single plane of focus for the background (far field) of an image, with a holographic display adapted to provide 3D objects in the foreground (near field). In an example of implementation, 3D imaging content can be adapted so that a dominant object can be provided in the foreground of the image, with other elements, such as scenery, provided in the image background. In the example, an object in the foreground would necessarily overlay elements in the background, resulting in ghosting and associated phenomena. In an example solution to this ghosting problem, 3D imaging content can be rendered so that little or no light can be

generated in the background provided by a 2D stereoscopic display in those areas that are overlaid by foreground elements.

[0099] In a specific related example, when the 2D stereoscopic display uses direct light emitting technology, such as an organic light-emitting diode (OLED) display, 3D imaging content can be rendered for each eye by a processor configured to generate foreground objects/content and background content. In another example, the occlusion is resolved so that little or no light can be emitted where a foreground object will be. In an alternative example, when the 2D stereoscopic display uses backlighting, such as a liquid crystal on silicon (LCos) display, backlighting in the background areas overlaid by foreground area can be reduced or eliminated. In another example, when a LCos display incorporates an active backplane, pixel elements overlaid by foreground objects can be shut off to prevent any contribution to ghosting.

[00100] In an example relevant to displays with both direct lighting and backlighting, an imaging mask (which can be dynamically programmed) can be provided to remove background light and in a specific related example, the boundary of foreground objects defined by the imaging mask can be adapted to provide varying amounts of foreground and background light to eliminate unnatural and/or annoying effects. In another example of implementation, a 3D imaging system can be configured so that a user's interpupillary distance can be accommodated with a mechanical or electronical adjustment. In another example of implementation, a measurement and calibration system can be added to a 3D display system to measure the interpupillary distance of the user and to calibrate the 3D display system to accommodate for this interpupillary distance in order for the 3D content, both foreground and background content, to blend together for the user.

[00101] In an example of implementation, calibration of a 3D display system for interpupillary distance can be done by taking the parameter of interpupillary distance into account in the algorithms and software executed to determine content to be displayed by the display(s) in the 3D display system.

[00102] **FIG. 9C** is a flowchart of a method for rendering and processing an image for 3D display. The method begins at step 420, where foreground elements are separated from the background of an image for display on a 3D optical display system. In an example, the foreground elements can be one or more dominant features associated with the image, with the background comprising the balance of the image (i.e. the portions of the image that are not dominant features). In an alternative example, the foreground elements can be predetermined and/or generated for use as foreground elements. In an example, separation of foreground elements from the background can include one or more of: processing the image to identify dominant features, determining foreground elements based on a predetermination, or selecting stored preexisting foreground elements. The method continues at step 402, with a determination of areas of background that will be overlaid by one or more foreground elements (occlusions). In an example, the determination of overlaid areas can be done using software tools associated with image rendering. In another example, the determination can be based on the separation process at step 420.

[00103] The method continues at step 424 with the background being processed to substantially remove light from pixels associated with overlaid areas. In an example, the processing can include generating a logical mask or template for use by a display device. In a related example, the mask can be adapted to provide information sufficient to enable processing of a foreground element boundary (or boundaries) for separate treatment. In a further related example, separate treatment of boundaries can include selective ghosting of the background at the foreground element boundaries. In yet a further related example, the selective ghosting can be dynamically altered to provide for more realistic display and/or to provide additional display effects.

[00104] At step 426, the method continues by displaying the background using one or more display devices. In an example, the one or more display devices are configured in a fixed focal plane. In an related example, the fixed focal

plane comprises one or more flat surfaces configured to be substantially perpendicular to the viewing direction of a person viewing the one or more display devices. At step 428, the foreground elements are projected using one or more spatial light modulators. In an example of implementation, the spatial light modulators are configured to project the foreground elements substantially perpendicular to the viewing direction of the eye(s) of a person viewing the one or more display devices. Example spatial light modulators are described elsewhere herein, along with reasonable alternatives.

[00105] Finally, at step 430 the method combines the projected foreground elements to overlay the previously processed areas of the background. In an example, the combining can be enabled using an optical element configured to place the foreground elements closer to the eye of a person viewing the one or more display devices, so that the foreground elements are placed to provide a relatively sharp image of the foreground elements on the fovea of the person's eye. In a related example, the method of FIG. 9C can be implemented for each eye of the hypothetical person viewing the one or more display devices.

[00106] In an example of implementation, the combining can be implemented using a partially reflective mirror, where the partially reflective mirror can be an optical element configured with a partially transmitting coating on a first surface and an antireflection coating on a second surface. In an example, when the angle of incidence (AOI) can be 0 degrees, the partially reflective mirror can be adapted to reflect at least a part of a light beam back. Referring again to FIG. 9A, a virtual reality (VR) system can include one or more two dimensional (2D) displays configured for use as a stereoscopic display, along with one or more spatial light modulators configured for use as holographic displays. In several examples, an illusion of 3D can be created by providing a slightly different image to each eye of a user.

[00107] In an example of implementation, a VR headset can be implemented as a 2D display configured as stereoscopic display, with the VR headset adapted to generate images that are slightly shifted relative to each other. Referring again to FIGs 2A and 2B, a given user's eyes can converge to perceive the depth of virtual objects will necessarily focus, or accommodate for a given fixed distance of a stereoscopic display. In various examples, this produces a mismatch between vergence and accommodation for a user, leading to visual discomfort, eye strain, and fatigue, as the natural coupling of vision processes can be disrupted.

[00108] In an example of implementation and operation, a virtual object displayed at a relatively large distance, such as 2 meters or more from a user, will present with an attenuated vergence accommodation conflict. In an example of operation, a holographic process can be adapted to mimic visual cues for a virtual object substantially as they would present from a real object. In some examples, the computation of hologram patterns for display can be computationally intensive, especially when the complexity and level of detail associated with a given 3D scene or image increases. In other examples, when hologram patterns are intended for real-time or low latency display, computational requirements can be particularly onerous.

[00109] In a specific example of implementation, a given holographic display can require a very high number of pixels relative to a non-holographic display having a same or similar resolution. In an example, a given holographic display can require multiple pixels to generate a single voxel. In various examples, a voxel (short for "volumetric pixel") can be used to represent a fundamental unit representing a point in 3D space. Accordingly, a voxel can be representative of a volume dimension for use generating three-dimensional images or holograms, whereas a two-dimensional 2D pixel is generally limited to the display of elements on a flat surface. In an example of implementation and operation, a voxel occupies a specific position within a three-dimensional grid, having an X, Y, and Z coordinate.

[00110] In various examples, a voxel can be used to represent the smallest distinguishable element that can be independently controlled to represent an element of 3D scene or image. In some examples, a voxel can have properties

such as color and brightness similar to a 2D pixel. In an example, a voxel's color and intensity can be adapted to enhance the overall appearance of a given hologram, providing depth and realism to a user's perception of a 3D scene or image. In an example of implementation and operation in holographic displays, voxels can be generated by modulating light at precise points within a display volume. In another example, modulating light at precise points can be implemented using interference patterns and/or other optical methods modified to enable light to be focused or diffused at specific locations, thereby generating a 3D object for perception by user. In various examples, the use of voxels can enable "volumetric imaging", where the entire volume of space within the display can be populated with voxels to form a completed 3D image viewable from different angles, just a real object can be viewed. In an example, the resolution of a holographic display can be provided as a number of voxels that can be rendered within a given volume.

[00111] In an example of implementation and operation, a VR headset can be implemented using a plurality of holographic displays to provide a 3D experience with, for example, one or more of less visual discomfort, less eye strain or less fatigue. In an example, display 3D content using a plurality of holographic displays can be difficult or impossible in a display system intend for real-time implementation. In an example of implementation and operation of a holographic display system, a 2D display can be configured to implement a stereoscopic display for display of virtual objects and/or virtual scenes at distances relatively far from the user (e.g. at distances of 2m or more), with one or more spatial light modulators configured as holographic display(s) for display of virtual objects relatively closer to a user's eyes.

[00112] In another related example, a holographic display system can be implemented with holographic display(s) for display of display virtual objects and/or virtual scenes in a foveated area (corresponding to the central 1-2 degrees of visual field) of a user. In an example, the foveation area of a given viewer's vision refers to the central region of the visual field where a viewer's eye's resolution and visual acuity are at a relative peak. In an example of implementation and operation, a holographic display system implemented with one or more stereoscopic displays for displaying virtual objects at a relative distance from a user can attenuate a vergence-accommodation conflict for a viewer.

[00113] In an example, one or more spatial light modulators configured as holographic displays for display of virtual objects close to the user, or in the foveated area of the user, can reduce computation requirements for rendering a 3D scene. Accordingly, combining a stereoscopic display and one or more spatial light modulators configured as holographic displays, can be used to overcome one or more limitations present in a holographic display system using only one of stereoscopic displays or one or more spatial light modulators configured as holographic display(s). In an example, the optical spectrum of both a 2D display and a spatial light modulator configured as holographic display system must be substantially the same, to effectively enable the combination of each in a holographic display system. In various examples, combining content for display by a 2D display having a different optical spectrum than a holographic display can lead to multiple display issues, including color inconsistency, metamerism, blending artifacts and color gamut differences.

[00114] In a specific example of implementation and operation, a stereoscopic display normally implemented by a generic 2D display device can be replaced with one or more spatial light modulators. In a specific related example, a spatial light modulator configured to function as a stereoscopic display need not require the same resolution as a spatial light modulator configured to display 3D objects, rather the stereoscopic display can be configured with relatively lower resolution and/or a larger pixel pitch. In another specific example, a holographic display system implemented using a spatial light modulator for each of stereoscopic display and holographic display by a spatial light modulator can be illuminated using a same or similar illumination source enabling a same or similar optical spectrum

for both the stereoscopic display and the holographic display. In various examples of implementation, a stereoscopic display can be implemented with a spatial light modulator based on Liquid Crystal on Silicon (LCoS) technology. In the example, LCOS based technology can provide sufficient resolution, with larger pixels that are acceptable stereoscopic display. In the various related examples, a holographic display can be implemented with a spatial light modulator configured with a pixel pitch smaller than the smallest desired wavelength of visible light, so that the holographic display system can be enabled to provide a sufficiently wide field of view.

[00115] In the example of **FIG. 10**, an x-cube beam splitter can be configured to use a single illumination source to illuminate both a spatial light modulator 440-B configured as a stereoscopic display and a spatial light modulator 440-A configured for holographic display. In the example, both the stereoscopic display 440-B and the holographic display 440-A can be adapted to provide substantially the same optical spectrum, while enabling combining virtual objects and/or virtual scenes display by the stereoscopic display, while 3D virtual objects are displayable by the holographic display. In an example, a spatial light modulator configured for holographic display can be configured with a color filter array overlaying light modulating elements. In a specific example, a color filter array of red, green, blue (RGB) or RGGB color filter mosaics can be used for holographic display, with a stereoscopic display configured without a color filter array overlaying the light modulating elements. In an example of operation, RGGB or RGB content can be created by time-multiplexing red, green and blue illumination for the stereoscopic display and the holographic display. In a specific related example, a holographic display implemented with a color filter array, along with a stereoscopic display having no associated color filter can be adapted to provide substantially the same optical spectrum. In the example, an illumination source can be configured to provide a narrower spectrum for each of the color channels, as compared to the spectrum of the red, green and blue color filter.

[00116] **FIG. 11** provides an illustration of another example virtual reality (VR) system arrangement that reduces or even eliminates vergence-accommodation conflict. The example VR system arrangement comprises one or more liquid crystal 2D displays configured as a 2D stereoscopic display and one or more holographic displays implemented with one or more spatial light modulators. In an example of implementation, the one or more liquid crystal 2D displays configured as a 2D stereoscopic display are employed to display virtual content in the “far” field / background (beyond ~1.5-2m distance) and the one or more holographic displays are employed to display virtual content in the “near” field / foreground (a distance of ~1.5-2m or less) or to display virtual content in the foveated area of the user.

[00117] In a related example of implementation and operation, eye tracking is adapted to the VR system arrangement to determine, among other things, the foveated area of the user. Example liquid crystal 2D displays comprise Twisted Nematic (TN) LCDs, In-Plane Switching (IPS) LCDs, Vertical Alignment (VA) LCDs, Super Twisted Nematic (STN) LCDs, Advanced Fringe Field Switching (AFFS) LCDs, Plane to Line Switching (PLS) LCDs and Multi-Domain Vertical Alignment (MVA) LCDs. In an example, the liquid crystal 2D display comprises a liquid crystal layer.

[00118] In a related example, the liquid crystal layer of the liquid crystal 2D display can be positioned between a common top electrode layer and an array of bottom electrodes, where each bottom electrode is associated with a thin-film transistor. The thin-film transistors, each associated with a single bottom electrode, control the voltage applied to the bottom electrodes relative to the voltage applied to the common top electrode layer. The voltage applied to a bottom electrode relative to the voltage of the common top electrode layer determines the electric field across the liquid crystal layer in the region associated with the bottom electrode. In a related example, the orientation of the liquid crystal molecules can be controlled by the application of an electric field. In case no electric field is applied across the liquid crystal layer, the liquid crystal molecules are aligned in a twisted configuration, which rotates the polarization of light as it passes through. In an example, when an electric field is applied across the liquid crystal

layer, the liquid crystal molecules align with the electric field, reducing or eliminating the rotation of the polarization of light as it passes through.

[00119] In an example, the backlight illumination is linearly polarized light. In a related example, the one or more liquid crystal 2D displays are provided with one or more illumination sources at the back surface of the one or more liquid crystal 2D displays to provide backlight illumination to the one or more liquid crystal 2D displays. In an example of implementation and operation, a first linear polarizing filter is applied above the top surface of the liquid crystal layer of the one or more liquid crystal 2D displays. In another related example, a second linear polarizing filter is applied in between the backlight illumination and the bottom surface of the liquid crystal layer of the one or more liquid crystal 2D displays, where the second polarizing filter is oriented at 90° to the first linear polarizing filter.

[00120] In an alternative example, the backlight illumination is unpolarized light. Unpolarized light as provided by the backlight illumination passes through the second polarizing filter, which is adapted between the backlight illumination and the bottom surface of the liquid crystal layer, resulting in linearly polarized light that is provided to the bottom surface of the liquid crystal layer. In an example, when no electric field is applied across the liquid crystal layer, the linearly polarized light passes through the liquid crystal layer, where the polarization of the light is typically rotated by 90°. In an example, when an electric field is applied across a region of the liquid crystal layer, linearly polarized light is rotated by less than 90° or not rotated at all, depending on the amount of electric field applied across the region of the liquid crystal layer. In an example, light that has passed through the liquid crystal layer reaches the first polarizing filter, adapted above the liquid crystal layer resulting in a polarization orientation orthogonal to the polarization orientation of the second polarizing filter, that has been implemented between the backlight illumination and the bottom surface of the liquid crystal layer.

[00121] In an example, when no electric field is applied across the liquid crystal layer, the polarization of the light is rotated by 90° after passing through the liquid crystal layer and as such the light is transmitted by the first polarizing filter, resulting in a bright pixel. In an example, an electric field can be applied across a region of the liquid crystal layer, forming a pixel for the liquid crystal 2D display, where the liquid crystals untwist, enabling polarization of light passed through that is rotated by less than 90°, with the result that part of the light is blocked by the first polarizing filter. In another example, when a large enough electric field is applied, liquid crystals are fully aligned, so that polarization of the light is achieved, resulting in light that is fully blocked by the first polarizing filter and resulting in “black” pixels. In an example, the grayscale of each pixel of the liquid crystal 2D display can be controlled by controlling the magnitude of the electric field applied across the liquid crystals corresponding to the associated pixel.

[00122] In a related example, the liquid crystal 2D display is configured to provide black pixels in the regions where the virtual content is to be displayed by the one or more holographic displays. In an example, the one or more holographic displays are implemented with one or more spatial light modulators. In a related example, the spatial light modulators configured as holographic display systems have a pixel pitch equal to or smaller than a wavelength of visible light. In another example, spatial light modulators configured as holographic display systems can have a pixel pitch equal to or smaller than half a wavelength of visible light. In the example, the one or more spatial light modulators operate in a reflective mode.

[00123] In the example of the VR system arrangement of FIG. 11, a quarter wave plate is adapted above the top surface of the one or more spatial light modulators, where the top surface comprises an array of light modulating elements. In a related example, a quarter wave plate comprises a birefringent material, with the birefringent material having two different refractive indices along two orthogonal axes. In a related example, light polarized along the axis of which the refractive index is lower travels faster than light polarized along the axis, orthogonal to the first axis, of which the refractive index is higher. In various examples, an axis along which light travels faster can be referred to

as the fast axis and the axis along which light travels slower can be referred to as the slow axis. In a related example, a quarter-wave plate converts linearly polarized light incident on the quarter-wave plate at a 45° angle to the fast and slow axes into circularly polarized light. In yet another related example, a quarter-wave plate converts circularly polarized light incident on the quarter-wave plate with the polarization components of the circularly polarized light aligned with the fast and slow axes of the quarter-wave plate into linearly polarized light.

[00124] In an example, an optical combiner can be adapted to the VR system arrangement of FIG. 9A, where the optical combiner merges the virtual content displayed by the stereoscopic display with the virtual content displayed by the one or more holographic displays for perception by the user of the VR system arrangement. In an example, the optical combiner adapted to the VR system arrangement of FIG. 11 can be implemented using a polarizing beam splitter 602. In an example, a polarizing beam splitter 602 passes light that is linearly polarized in a first direction and reflects light that is linearly polarized in a second direction that is orthogonal to the first direction. In yet another example, the VR system arrangement of FIG. 11 further comprises an illumination source 604. In a related example, the illumination source 604 is an illumination source providing both red, green and blue light.

[00125] In another related example, the illumination source 604 provides linearly polarized light. In the example of the VR system arrangement of FIG. 11, light generated by the illumination source 604 has a polarization direction that matches the polarization direction for which the polarizing beam splitter 602 passes light. In a related example, polarizing beam splitter 602 is adapted to pass light from illumination source 604 to the one or more spatial light modulators 606 configured as holographic display(s). In an example, linearly polarized light provided by the illumination source 604 and passed by the polarizing beam splitter 602 is incident to a quarter-wave plate 608 adapted above the top surface of the one or more spatial light modulators 606 with the polarization direction of the linearly polarized light at a 45° angle to the fast and slow axes of the quarter-wave plate 608.

[00126] In an example, linearly polarized light incident to the quarter-wave plate at a 45° angle to the fast and slow axes of the quarter-wave plate passes through the quarter-wave plate with the quarter-wave plate, converting the linearly polarized light into circularly polarized light. In a related example, the circularly polarized light reaches light modulating elements of the one or more spatial light modulators 606 such that the circularly polarized light is modulated and reflected toward a bottom surface of the quarter-wave plate 608 by the light modulating elements. In an example, reflection of circularly polarized light towards the bottom surface of the quarter-wave plate 608, a “handedness” of the circular polarization (right-handed or left-handed) is maintained.

[00127] In a related example, light reflected toward the bottom surface of the quarter-wave plate 608, having an opposite-handed circular polarization relative to the circular polarization of light incident to the light modulating elements of the one or more spatial light modulators 606, passes through the quarter-wave plate 608 a second time, with quarter-wave plate 608 converting the circularly polarized light to linearly polarized light, where the polarization direction is 90° rotated relative to the polarization direction of the linearly polarized light incident to the top surface of the quarter wave plate 608. In an example, 90° rotated linearly polarized light is directed to the polarizing beam splitter 602 with the polarizing beam splitter 602 reflecting the 90° -rotated linearly polarized light to a user's eyes as the polarization direction of the light 90° -rotated linearly polarized reaching the polarizing beam splitter 602 is orthogonal to the direction to which the polarizing beam splitter is 602 is transmissive.

[00128] In an example, light transmitted by 2D liquid crystal (LCD) display 610 is linearly polarized, with the polarization direction of the light matching the direction at which the polarizing beam splitter 602 transmits light. The wavefronts of the 2D LCD display 210 passed by the polarizing beam splitter 602 can be combined with wavefronts from one or more holographic displays 606, which are reflected by the polarizing beam splitter 602, such that a user

can perceive both the virtual content as displayed by the 2D stereoscopic display and virtual content displayed by the one or more holographic displays 606.

[00129] In an example, the polarizing beam splitter 602 can be implemented with a wire grid polarizer, where the wire grid polarizer comprises a grid of fine, parallel wires. In a related example, the backlight illumination 612 of the liquid crystal 2D display and the illumination source 604 which provides illumination to the one or more holographic displays can be adapted to have approximately the same spectrum (approximately the same spectral distribution). In a related example, a spatially-varying color filter pattern can be adapted for use on the liquid crystal 2D display 610. In another related example, each pixel of a liquid crystal 2D display 610 can comprise three individually-controllable subpixels: a subpixel with a red color filter, a subpixel with a green color filter and a subpixel with a blue color filter.

[00130] In an example, a spatially-varying color filter pattern can be adapted for implementation atop the light modulating elements of the one or more holographic displays. In a related example, a spatially-varying color filter pattern implemented atop light modulating elements of the one or more holographic displays, can comprise a set of subareas, with each subarea adapted to be one of: 1) transparent as to red light and blocking/absorptive as to green and blue light; 2) transparent as to green light and blocking/absorptive as to red and blue light; or 3) transparent as to blue light and blocking/absorptive as to red and green light. In a related example, an illumination source used to provide illumination to one or more holographic displays can be configured to provide time-multiplexing of red, green and blue illumination.

[00131] In an alternative example, one or more holographic displays can be integrated to interact with red light only, with one or more holographic displays integrated to interact with green light only and one or more holographic displays integrated to interact with blue light only. In an example, an example virtual reality (VR) system can be configured to reduce or even eliminates vergence-accommodation conflict.

[00132] FIG. 12 provides an illustration of another example virtual reality (VR) system, with a virtual reality system, such as virtual reality system 620, configured with a reflective liquid crystal 2D display 630 for stereoscopic display (as opposed to the transmissive liquid crystal 2D display illustrated in FIG. 11). In a related example, one or more LCoS displays configured to operate as reflective displays, or any other type of reflective spatial light modulating display can be used in a virtual reality (VR) system. In another related example, an illumination source 628 can be adapted to provide illumination for both the stereoscopic display and for the one or more holographic displays. In an example of implementation and operation, unpolarized light "1" is projected at polarizing beam splitter 624 with the polarizing beam splitter 624 passing light "3" with a first polarization direction to the one or more holographic displays (spatial light modulator 622) and reflects light with a second polarization direction "2", orthogonal to the first polarization direction, to the stereoscopic display (reflective LCD display 630). In an example of operation and implementation, the reflective LCD display 630, comprises a liquid crystal layer, where an electric field applied across each region of the liquid crystal layer controls the polarization direction of light exiting that region of the reflective LCD display 630. In an example, reflective LCD display 630 modulates the polarization of an incoming light field to control which part of the light field is transmitted by the polarizing beam splitter for perception by a user and which part of the light field is reflected so that it is not perceivable by a user. In an example, spatial light modulator 622 operates in a same or similar manner as the one or more holographic displays of FIG. 11. Polarizing beam splitter 624 is adapted to combine virtual content displayed by reflective LCD display 630 and the virtual content displayed by spatial light modulator 622 (which can include one or more holographic displays) for perception by a user of the VR system arrangement.

[00133] It is noted that terminologies as may be used herein such as bit stream, stream, signal sequence, etc. (or their equivalents) have been used interchangeably to describe digital information whose content corresponds to any of a

number of desired types (e.g., data, video, speech, text, graphics, audio, etc. any of which may generally be referred to as ‘data’). As may also be used herein, a hologram pattern or hologram refers to a light interference pattern, while a hologram pattern is a diffraction pattern that diffracts incident light. Further, a holographic image refers to the visual result perceivable by a viewer when a hologram pattern is properly illuminated. As such the visual result perceivable by a viewer includes two-dimensional (2D) images, two-dimensional (2D) representations, two-dimensional (2D) information, three-dimensional (3D) objects and three-dimensional (3D) scenes.

[00134] As may be used herein, the terms “substantially” and “approximately” provide an industry-accepted tolerance for its corresponding term and/or relativity between items. For some industries, an industry-accepted tolerance is less than one percent and, for other industries, the industry-accepted tolerance is 10 percent or more. Other examples of industry-accepted tolerance range from less than one percent to fifty percent. Industry-accepted tolerances correspond to, but are not limited to, component values, integrated circuit process variations, temperature variations, rise and fall times, thermal noise, dimensions, signaling errors, dropped packets, temperatures, pressures, material compositions, and/or performance metrics. Within an industry, tolerance variances of accepted tolerances may be more or less than a percentage level (e.g., dimension tolerance of less than +/- 1%). Some relativity between items may range from a difference of less than a percentage level to a few percent. Other relativity between items may range from a difference of a few percent to magnitude of differences.

[00135] As may also be used herein, the term(s) “configured to”, “operably coupled to”, “coupled to”, and/or “coupling” includes direct coupling between items and/or indirect coupling between items via an intervening item (e.g., an item includes, but is not limited to, a component, an element, a circuit, and/or a module) where, for an example of indirect coupling, the intervening item does not modify the information of a signal but may adjust its current level, voltage level, and/or power level. As may further be used herein, inferred coupling (i.e., where one element is coupled to another element by inference) includes direct and indirect coupling between two items in the same manner as “coupled to”.

[00136] As may even further be used herein, the term “configured to”, “operable to”, “coupled to”, or “operably coupled to” indicates that an item includes one or more of power connections, input(s), output(s), etc., to perform, when activated, one or more its corresponding functions and may further include inferred coupling to one or more other items. As may still further be used herein, the term “associated with”, includes direct and/or indirect coupling of separate items and/or one item being embedded within another item.

[00137] As may be used herein, the term “compares favorably”, indicates that a comparison between two or more items, signals, etc., indicates an advantageous relationship that would be evident to one skilled in the art in light of the present disclosure, and based, for example, on the nature of the signals/items that are being compared. As may be used herein, the term “compares unfavorably”, indicates that a comparison between two or more items, signals, etc., fails to provide such an advantageous relationship and/or that provides a disadvantageous relationship. Such an item/signal can correspond to one or more numeric values, one or more measurements, one or more counts and/or proportions, one or more types of data, and/or other information with attributes that can be compared to a threshold, to each other and/or to attributes of other information to determine whether a favorable or unfavorable comparison exists. Examples of such an advantageous relationship can include: one item/signal being greater than (or greater than or equal to) a threshold value, one item/signal being less than (or less than or equal to) a threshold value, one item/signal being greater than (or greater than or equal to) another item/signal, one item/signal being less than (or less than or equal to) another item/signal, one item/signal matching another item/signal, one item/signal substantially matching another item/signal within a predefined or industry accepted tolerance such as 1%, 5%, 10% or some other margin, etc. Furthermore, one skilled in the art will recognize that such a comparison between two items/signals can

be performed in different ways. For example, when the advantageous relationship is that signal 1 has a greater magnitude than signal 2, a favorable comparison may be achieved when the magnitude of signal 1 is greater than that of signal 2 or when the magnitude of signal 2 is less than that of signal 1. Similarly, one skilled in the art will recognize that the comparison of the inverse or opposite of items/signals and/or other forms of mathematical or logical equivalence can likewise be used in an equivalent fashion. For example, the comparison to determine if a signal $X > 5$ is equivalent to determining if $-X < -5$, and the comparison to determine if signal A matches signal B can likewise be performed by determining $-A$ matches $-B$ or $\text{not}(A)$ matches $\text{not}(B)$. As may be discussed herein, the determination that a particular relationship is present (either favorable or unfavorable) can be utilized to automatically trigger a particular action. Unless expressly stated to the contrary, the absence of that particular condition may be assumed to imply that the particular action will not automatically be triggered. In other examples, the determination that a particular relationship is present (either favorable or unfavorable) can be utilized as a basis or consideration to determine whether to perform one or more actions. Note that such a basis or consideration can be considered alone or in combination with one or more other bases or considerations to determine whether to perform the one or more actions. In one example where multiple bases or considerations are used to determine whether to perform one or more actions, the respective bases or considerations are given equal weight in such determination. In another example where multiple bases or considerations are used to determine whether to perform one or more actions, the respective bases or considerations are given unequal weight in such determination.

[00138] As may be used herein, one or more claims may include, in a specific form of this generic form, the phrase “at least one of a, b, and c” or of this generic form “at least one of a, b, or c”, with more or less elements than “a”, “b”, and “c”. In either phrasing, the phrases are to be interpreted identically. In particular, “at least one of a, b, and c” is equivalent to “at least one of a, b, or c” and shall mean a, b, and/or c. As an example, it means: “a” only, “b” only, “c” only, “a” and “b”, “a” and “c”, “b” and “c”, and/or “a”, “b”, and “c”.

[00139] As may also be used herein, the terms “processing module”, “processing circuit”, “processor”, “processing circuitry”, and/or “processing unit” may be a single processing device or a plurality of processing devices. Such a processing device may be a microprocessor, micro-controller, digital signal processor, microcomputer, central processing unit, field programmable gate array, programmable logic device, state machine, logic circuitry, analog circuitry, digital circuitry, and/or any device that manipulates signals (analog and/or digital) based on hard coding of the circuitry and/or operational instructions. The processing module, module, processing circuit, processing circuitry, and/or processing unit may be, or further include, memory and/or an integrated memory element, which may be a single memory device, a plurality of memory devices, and/or embedded circuitry of another processing module, module, processing circuit, processing circuitry, and/or processing unit. Such a memory device may be a read-only memory, random access memory, volatile memory, non-volatile memory, static memory, dynamic memory, flash memory, cache memory, and/or any device that stores digital information. Note that if the processing module, module, processing circuit, processing circuitry, and/or processing unit includes more than one processing device, the processing devices may be centrally located (e.g., directly coupled together via a wired and/or wireless bus structure) or may be distributedly located (e.g., cloud computing via indirect coupling via a local area network and/or a wide area network). Further note that if the processing module, module, processing circuit, processing circuitry and/or processing unit implements one or more of its functions via a state machine, analog circuitry, digital circuitry, and/or logic circuitry, the memory and/or memory element storing the corresponding operational instructions may be embedded within, or external to, the circuitry comprising the state machine, analog circuitry, digital circuitry, and/or logic circuitry. Still further note that, the memory element may store, and the processing module, module, processing circuit, processing circuitry and/or processing unit executes, hard coded and/or operational instructions corresponding

to at least some of the steps and/or functions illustrated in one or more of the Figures. Such a memory device or memory element can be included in an article of manufacture.

[00140] One or more embodiments have been described above with the aid of method steps illustrating the performance of specified functions and relationships thereof. The boundaries and sequence of these functional building blocks and method steps have been arbitrarily defined herein for convenience of description. Alternate boundaries and sequences can be defined so long as the specified functions and relationships are appropriately performed. Any such alternate boundaries or sequences are thus within the scope and spirit of the claims. Further, the boundaries of these functional building blocks have been arbitrarily defined for convenience of description. Alternate boundaries could be defined as long as the certain significant functions are appropriately performed. Similarly, flow diagram blocks may also have been arbitrarily defined herein to illustrate certain significant functionality.

[00141] To the extent used, the flow diagram block boundaries and sequence could have been defined otherwise and still perform the certain significant functionality. Such alternate definitions of both functional building blocks and flow diagram blocks and sequences are thus within the scope and spirit of the claims. One of average skill in the art will also recognize that the functional building blocks, and other illustrative blocks, modules and components herein, can be implemented as illustrated or by discrete components, application specific integrated circuits, processors executing appropriate software and the like or any combination thereof.

[00142] In addition, a flow diagram may include a “start” and/or “continue” indication. The “start” and “continue” indications reflect that the steps presented can optionally be incorporated in or otherwise used in conjunction with one or more other routines. In addition, a flow diagram may include an “end” and/or “continue” indication. The “end” and/or “continue” indications reflect that the steps presented can end as described and shown or optionally be incorporated in or otherwise used in conjunction with one or more other routines. In this context, “start” indicates the beginning of the first step presented and may be preceded by other activities not specifically shown. Further, the “continue” indication reflects that the steps presented may be performed multiple times and/or may be succeeded by other activities not specifically shown. Further, while a flow diagram indicates a particular ordering of steps, other orderings are likewise possible provided that the principles of causality are maintained.

[00143] The one or more embodiments are used herein to illustrate one or more aspects, one or more features, one or more concepts, and/or one or more examples. A physical embodiment of an apparatus, an article of manufacture, a machine, and/or of a process may include one or more of the aspects, features, concepts, examples, etc. described with reference to one or more of the embodiments discussed herein. Further, from figure to figure, the embodiments may incorporate the same or similarly named functions, steps, modules, etc. that may use the same or different reference numbers and, as such, the functions, steps, modules, etc. may be the same or similar functions, steps, modules, etc. or different ones.

[00144] Unless specifically stated to the contra, signals to, from, and/or between elements in a figure of any of the figures presented herein may be analog or digital, continuous time or discrete time, and single-ended or differential. For instance, if a signal path is shown as a single-ended path, it also represents a differential signal path. Similarly, if a signal path is shown as a differential path, it also represents a single-ended signal path. While one or more particular architectures are described herein, other architectures can likewise be implemented that use one or more data buses not expressly shown, direct connectivity between elements, and/or indirect coupling between other elements as recognized by one of average skill in the art.

[00145] The term “module” is used in the description of one or more of the embodiments. A module implements one or more functions via a device such as a processor or other processing device or other hardware that may include

or operate in association with a memory that stores operational instructions. A module may operate independently and/or in conjunction with software and/or firmware. As also used herein, a module may contain one or more sub-modules, each of which may be one or more modules.

[00146] As may further be used herein, a computer readable memory includes one or more memory elements. A memory element may be a separate memory device, multiple memory devices, or a set of memory locations within a memory device. Such a memory device may be a read-only memory, random access memory, volatile memory, non-volatile memory, static memory, dynamic memory, flash memory, cache memory, a quantum register or other quantum memory and/or any other device that stores data in a non-transitory manner. Furthermore, the memory device may be in a form of a solid-state memory, a hard drive memory or other disk storage, cloud memory, thumb drive, server memory, computing device memory, and/or other non-transitory medium for storing data. The storage of data includes temporary storage (i.e., data is lost when power is removed from the memory element) and/or persistent storage (i.e., data is retained when power is removed from the memory element). As used herein, a transitory medium shall mean one or more of: (a) a wired or wireless medium for the transportation of data as a signal from one computing device to another computing device for temporary storage or persistent storage; (b) a wired or wireless medium for the transportation of data as a signal within a computing device from one element of the computing device to another element of the computing device for temporary storage or persistent storage; (c) a wired or wireless medium for the transportation of data as a signal from one computing device to another computing device for processing the data by the other computing device; and (d) a wired or wireless medium for the transportation of data as a signal within a computing device from one element of the computing device to another element of the computing device for processing the data by the other element of the computing device. As may be used herein, a non-transitory computer readable memory is substantially equivalent to a computer readable memory. A non-transitory computer readable memory can also be referred to as a non-transitory computer readable storage medium.

[00147] One or more functions associated with the methods and/or processes described herein can be implemented via a processing module that operates via the non-human “artificial” intelligence (AI) of a machine. Examples of such AI include machines that operate via anomaly detection techniques, decision trees, association rules, expert systems and other knowledge-based systems, computer vision models, artificial neural networks, convolutional neural networks, support vector machines (SVMs), Bayesian networks, genetic algorithms, feature learning, sparse dictionary learning, preference learning, deep learning and other machine learning techniques that are trained using training data via unsupervised, semi-supervised, supervised and/or reinforcement learning, and/or other AI. The human mind is not equipped to perform such AI techniques, not only due to the complexity of these techniques, but also due to the fact that artificial intelligence, by its very definition – requires “artificial” intelligence – i.e., machine/non-human intelligence.

[00148] One or more functions associated with the methods and/or processes described herein can be implemented as a large-scale system that is operable to receive, transmit and/or process data on a large-scale. As used herein, a large-scale refers to a large number of data, such as one or more kilobytes, megabytes, gigabytes, terabytes or more of data that are received, transmitted and/or processed. Such receiving, transmitting and/or processing of data cannot practically be performed by the human mind on a large-scale within a reasonable period of time, such as within a second, a millisecond, microsecond, a real-time basis or other high speed required by the machines that generate the data, receive the data, convey the data, store the data and/or use the data.

[00149] One or more functions associated with the methods and/or processes described herein can require data to be manipulated in different ways within overlapping time spans. The human mind is not equipped to perform such different data manipulations independently, contemporaneously, in parallel, and/or on a coordinated basis within a

reasonable period of time, such as within a second, a millisecond, microsecond, a real-time basis or other high speed required by the machines that generate the data, receive the data, convey the data, store the data and/or use the data.

[00150] One or more functions associated with the methods and/or processes described herein can be implemented in a system that is operable to electronically receive digital data via a wired or wireless communication network and/or to electronically transmit digital data via a wired or wireless communication network. Such receiving and transmitting cannot practically be performed by the human mind because the human mind is not equipped to electronically transmit or receive digital data, let alone to transmit and receive digital data via a wired or wireless communication network.

[00151] One or more functions associated with the methods and/or processes described herein can be implemented in a system that is operable to electronically store digital data in a memory device. Such storage cannot practically be performed by the human mind because the human mind is not equipped to electronically store digital data.

[00152] One or more functions associated with the methods and/or processes described herein may operate to cause an action by a processing module directly in response to a triggering event -- without any intervening human interaction between the triggering event and the action. Any such actions may be identified as being performed “automatically”, “automatically based on” and/or “automatically in response to” such a triggering event. Furthermore, any such actions identified in such a fashion specifically preclude the operation of human activity with respect to these actions – even if the triggering event itself may be causally connected to a human activity of some kind.

[00153] While particular combinations of various functions and features of the one or more embodiments have been expressly described herein, other combinations of these features and functions are likewise possible. The present disclosure is not limited by the particular examples disclosed herein and expressly incorporates these other combinations.

CLAIMS

What is claimed is:

1. A light modulating device comprises:

- 5 a substrate having a respective top surface and a respective bottom surface;
 a plurality of electrical interconnects disposed in the top surface of the substrate;
 a plurality of first electrodes arranged on the substrate, each first electrode of the plurality
 of first electrodes having a respective top and a respective bottom, wherein the bottom of each first
 electrode is coupled to an electrical interconnect of the plurality of electrical interconnects, wherein
 10 each first electrode is electrically isolated from every other first electrode of the plurality of first
 electrodes;
 a first dielectric layer having a respective top surface and a respective bottom surface, the
 bottom surface of the first dielectric layer located atop the plurality of first electrodes;
 a quantum well layer having a respective top surface and a respective bottom surface, the
 15 bottom surface of the quantum well layer overlaying the top surface of the first dielectric layer;
 a second dielectric layer having a respective top surface and a respective bottom surface,
 the bottom surface of the second dielectric layer overlaying the top surface of the quantum well
 layer; and
 a second electrode having a respective top surface and a respective bottom surface, the
 20 bottom surface of the second electrode overlaying the top surface of the second dielectric layer.

2. The light modulating device of claim 1, wherein the first dielectric layer, the quantum well layer and the
 second dielectric layer together comprise a plurality of quantum well stacks, wherein each quantum well stack of the
 plurality of quantum well stacks is spatially separated from every other quantum well stack of the plurality of quantum
 25 well stacks, wherein the first dielectric layer of each quantum well stack is coupled to a first electrode of the plurality
 of first electrodes, wherein the second dielectric layer of each quantum well stack is coupled to the second electrode.

3. A light modulating device comprises:

- a substrate having a respective top surface and a respective bottom surface;
 30 a plurality of electrical interconnects disposed in the top surface of the substrate;
 an array of light modulating elements, with the light modulating elements of the array of light
 modulating elements having a respective top and a respective bottom,
 wherein a light modulating element of the array of light modulating elements comprises
 a bottom electrode arranged on the substrate, with the bottom electrode having a respective top and
 35 a respective bottom, wherein the bottom of the bottom electrode is coupled to an electrical interconnect of
 the plurality of electrical interconnects;
 a first dielectric layer having a respective top surface and a respective bottom surface, the bottom
 surface of the first dielectric layer located over the bottom electrode;
 a quantum well layer having a respective top surface and a respective bottom surface, the bottom
 40 surface of the quantum well layer overlaying the top surface of the first dielectric layer;
 a second dielectric layer having a respective top surface and a respective bottom surface, the bottom
 surface of the second dielectric layer overlaying the top surface of the quantum well layer;

wherein each light modulating element of the array of light modulating elements is spatially separated from every other light modulating element of the array;

and a top electrode located over the top of one or more light modulating elements of the array of light modulating elements.

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4. The light modulating device of claim 3, wherein a light modulating element of the array of light modulating elements comprises a bottom electrode, the first dielectric layer, a quantum well layer and the second dielectric layer, with the first dielectric layer, the quantum well layer and the second dielectric layer together forming a quantum well structure.

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5. The light modulating device of claim 4, wherein a quantum well structure is spatially separated from every other quantum well structure by an isolation structure.

6. The light modulating device of claim 3, wherein each light modulating element of the array of light modulating elements is spatially separated from every other light modulating element of the array of light modulating elements by an isolation structure.

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7. The light modulating device of claim 6, wherein the isolation structure comprises at least one of a metal material, a semiconducting material, a low resistance conducting material or a high resistance conducting material.

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8. The light modulating device of claim 6, wherein the isolation structure is electrically coupled to the top electrode as located over the top of one or more light modulating elements of the array of light modulating elements.

9. The light modulating device of claim 6, wherein an electric potential can be applied to the isolation structure, wherein the electric potential is independently controllable.

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10. The light modulating device of claim 3, further comprising:
another quantum well layer having a respective top surface and a respective bottom surface.

11. The light modulating device of claim 3, wherein the quantum well layer has a thickness equal to or smaller than 10 nm.

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12. The light modulating device of claim 3, wherein the quantum well layer includes at least one of gold (Au), platinum (Pt), silver (Ag) aluminum (Al), silicon (Si), germanium (Ge) or a III-V compound.

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13. The light modulating device of claim 3, wherein each of the first and second dielectric layers have a thickness equal to or smaller than 20 nm.

14. The light modulating device of claim 3, wherein each of the first and second dielectric layers include at least one of silicon dioxide (SiO₂), silicon nitride (Si₃N₄) or aluminum oxide (Al₂O₃).

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15. The light modulating device of claim 3, wherein the top electrode is substantially transparent to visible light.

16. The light modulating device of claim 3, further comprising:

a third electrode having a respective top surface and a respective bottom surface, the bottom surface of the third electrode overlaying the top of the plurality of first electrodes and the bottom surface of the first dielectric layer overlaying the top surface of the third electrode.

17. The light modulating device of claim 16, wherein the third electrode comprises a high resistive conducting material, including high resistive metal materials, high resistive semimetal material and high resistive semiconducting materials.

18. The light modulating device of claim 3, wherein an electric potential can be applied to one or more first electrodes of the plurality of first electrodes and to the second electrode, wherein the electric potential applied to each of the one or more first electrodes and the second electrode is adapted to be independently controllable.

19. The light modulating device of claim 3, wherein the pitch of two adjacent first electrodes of the plurality of first electrodes is equal to or smaller than a wavelength of visible light used with the device.

20. The light modulating device of claim 3, wherein the plurality of first electrodes are arranged in one of a square grid structure, a staggered grid structure or a hexagonal grid structure.

21. The light modulating device of claim 4, wherein the pitch of two adjacent light modulating elements of the array of light modulating elements is equal to or smaller than a wavelength of visible light used with the device, preferably equal to or smaller than half a wavelength of visible light used with the device.

22. A light modulating device comprises:

a substrate having a respective top surface and a respective bottom surface;

a plurality of electrical interconnects disposed in the top surface of the substrate;

a plurality of first electrodes arranged on a substrate, each first electrode of the plurality of first electrodes having a respective top and a respective bottom, wherein the bottom of each first electrode is coupled to an electrical interconnect of the plurality of electrical interconnects, wherein each first electrode is electrically isolated from every other first electrode of the plurality of first electrodes;

a phase change layer having a respective top surface and a respective bottom surface, the bottom surface of the phase change layer overlaying the top surface of the plurality of first electrodes; and

an second electrode having a respective top surface and a respective bottom surface, the bottom surface of the second electrode located atop the top surface of the phase change layer.

23. The light modulating device of claim 22, wherein a top portion of each electrode of the plurality of first electrodes is adapted to cause heat generation.

24. The light modulating device of claim 22, wherein a top portion of each electrode of the plurality of electrodes comprises a high resistivity conducting material.

25. The light modulating device of claim 22, wherein the second electrode is adapted to be substantially adapted to visible light.

26. The light modulating device of claim 22, wherein the phase change layer includes at least one of a chalcogenide phase change material, germanium-antimony-tellurium ($\text{Ge}_x\text{Sb}_y\text{Te}_z$), antimony sulfide (Sb_xS_y), antimony selenide (Sb_xSe_y) or molybdenum oxide (Mo_xO_y).

27. The light modulating device of claim 22, wherein an electric potential can be applied to one or more first electrodes of the plurality of first electrodes and to the second electrode, wherein the electric potential applied to each of the one or more first electrodes and the second electrode is adapted to be independently controllable.

28. The light modulating device of claim 22, wherein a pitch space between two adjacent first electrodes of the plurality of first electrodes is equal to or smaller than a wavelength of visible light.

29. The light modulating device of claim 22, wherein the plurality of first electrodes are arranged in one of a square grid structure, a staggered grid structure or a hexagonal grid structure.

30. The light modulating device of claim 22, wherein the phase change layer is adapted to change from a first state to a second state.

31. The light modulating device of claim 22, wherein a current flow between a first electrode of the plurality of first electrodes and the second electrode is independently controllable, wherein a portion of the phase change layer is adapted to change from a first state to a second state in response to current flow and wherein a size of the portion is based on a relative amplitude or duration of the current flow.

32. The light modulation device of claim 31, wherein size of the portion causes the phase change layer to exhibit a different light modulating property.

33. A light modulating device comprises:

a substrate having a respective top surface and a respective bottom surface;

a plurality of electrical interconnects disposed in the top surface of the substrate;

a plurality of first electrodes arranged on a substrate, each first electrode of the plurality of first electrodes having a respective top and a respective bottom, wherein the bottom of a first electrode is coupled to an electrical interconnect of the plurality of electrical interconnects, wherein each first electrode is electrically isolated from every other first electrode of the plurality of first electrodes;

a plurality of spatially separated heater elements, arranged in an array, each heater element having a respective top and a respective bottom, wherein the bottom of each heater element of the plurality of heater elements is coupled to a first electrode and to a second electrode of the plurality of electrodes, wherein the first electrode and second electrodes are configured to enable current flow there-between; and

a phase change layer having a respective top surface and a respective bottom surface, the bottom surface of the phase change layer overlaying the top surface of the plurality of heater elements.

34. The light modulating device of claim 33, further comprising:
an insulating layer having a respective top surface and a respective bottom surface, the bottom surface of the insulating layer overlaying the top of the plurality of heater elements and the bottom surface of the phase change layer overlaying the top surface of the insulating layer.

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35. The light modulating device of claim 33, wherein the heater elements of the plurality of heater elements comprise a high resistive conducting material.

36. The light modulating device of claim 33, wherein the phase change layer including at least one of a chalcogenide phase change material, germanium-antimony-tellurium (GeSbTe), antimony sulfide (Sb₂S₃), antimony selenide (Sb₂Se₃) and molybdenum oxide (MoO₃).

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37. The light modulating device of claim 33, wherein one or more heater elements of the plurality of heater elements exhibit one of a void, a U-shape or an S-shape.

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38. The light modulating device of claim 33, wherein a pitch space between two adjacent heater elements of the plurality of heater elements is equal to or smaller than a wavelength of visible light.

39. The light modulating device of claim 33, wherein the phase change layer is adapted to change between a first state to a second state.

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40. An optical display system comprising:
one or more arrays of light modulating elements configured to display a holographic image;
one or more display elements configured as a stereoscopic display for displaying a stereoscopic
image; and
one or more optical elements configured to viewably combine the holographic image and the
stereoscopic image.

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41. The optical display system of claim 40, further comprising one or more illumination sources.

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42. The optical display system of claim 40, wherein an illumination source of the one or more illumination sources is configured to provide at least one of linearly polarized light or circularly polarized light.

43. The optical display system of claim 40, wherein the one or more illumination sources are adapted to provide illumination for an array of the one or more arrays of light modulating elements, wherein the array is configured to display a holographic image and wherein at least one of the one or more illumination sources is adapted to provide illumination to one or more display elements configured to provide stereoscopic display.

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44. The optical display system of claim 43, wherein each illumination source of the one or more illumination sources is adapted to provide light of a same spectral frequency.

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45. The optical display system of claim 43, further comprising:

a spatially varying color filter pattern configured proximal to one or more arrays of light modulating elements, wherein the filters and the to one or more arrays of light modulating elements together are adapted to display a holographic image.

5 46. The optical display system of claim 45, wherein the spatially varying color filter pattern comprises a red filter, a green filter and a blue filter; wherein the red filter is transparent to red light, but absorbing for green and blue light, wherein the green filter is transparent to green light, but absorbing for red and blue light, and wherein the blue filter is transparent to blue light, but absorbing for red and green light.

10 47. The optical display system of claim 41, wherein the one or more illumination sources are configured to provide at least one of red light, green light or blue light.

48. The optical display system of claim 40, wherein the one or more optical elements are configured to viewably combine the holographic image and the stereoscopic image and to direct an illumination of the one or more
15 illumination sources to at least one of the one or more arrays of light modulating elements configured to display a holographic image to at least one of the one or more arrays of light modulating elements configured as a stereoscopic display.

49. The optical display system of claim 40, wherein the optical display system is configured to interact with data
20 representative of media for display, wherein the media for display includes foreground elements and background elements and wherein the one or more arrays of light modulating elements are adapted to render, based on the data, the foreground elements in the form of a holographic image and wherein the one or more display elements are configured to render, based on the data, the background elements.

25 50. The optical display system of claim 40, wherein the one or more arrays of light modulating elements are configured to render a holographic image in a region corresponding with a foveated area of a user and wherein the one or more display elements are configured to render a stereoscopic image in a region outside the foveated area.

51. The optical display system of claim 40, wherein the one or more display elements configured as a
30 stereoscopic display are configured to provide black pixels in a region corresponding with a region where the one or more arrays of light modulating elements displays a holographic image.

52. The optical display system of claim 40, wherein a holographic image is at least one of a two-dimensional (2D) image, a two-dimensional (2D) representation, two-dimensional (2D) information, a three-dimensional (3D)
35 object or a three-dimensional (3D) scene.

53. The optical display system of claim 40, further comprising one or more processing modules of one or more processors configured to execute one or more Computer-Generated Holography computer generated holography (CGH) algorithms to generate hologram patterns.

40 54. The optical display system of claim 53, wherein the one or more CGH algorithms include at least one of a Fourier transform algorithm, a Fresnel transform algorithm, an iterative Fourier transform algorithm (ITFA), a point

cloud method-based algorithm, an angular spectrum method-based algorithm, or a look-up table (LUT) method-based algorithm.

55. The optical display system of claim 53, further comprising memory adapted to store one or more computed
5 hologram patterns.

56. The optical display system of claim 53, wherein the hologram patterns include holographic interference patterns.

10 57. The optical display system of claim 40, wherein a distance between centers of adjacent light modulating elements of the array is equal to or less than a half wavelength of visible light.

58. The optical display system of claim 40, further comprising:
a measurement and calibration system adapted to determine an interpupillary distance of a user,
15 wherein the measurement and calibration system is further adapted to calibrate the optical display system based on the interpupillary distance.

59. The optical display system of claim 40, wherein the stereoscopic media includes background media and holographic media.
20

60. The optical display system of claim 40, wherein a stereoscopic display element of the one or more stereoscopic display elements is implemented with a liquid crystal on silicon (LCoS) display.

61. The optical display system of claim 60, wherein the liquid crystal on silicon (LCoS) display has a respective
25 top surface and a respective bottom surface, wherein a polarizing filter is implemented over the top surface.

62. The optical display system of claim 40, wherein the one or more optical elements are further configured to facilitate illuminating the one or more display elements configured as a stereoscopic display and the one or more arrays of light modulating elements configured to display a holographic image with a same illumination source.
30

63. The optical display system of claim 62, further comprising:
an x-cube beam splitter.

64. The optical display system of claim 40, wherein the one or more display elements configured as a
35 stereoscopic display comprise one or more arrays of light modulating elements that are different from the one or more arrays of light modulating elements configured to display a holographic image.

65. The optical display system of claim 40, further comprising an eye tracking element.

40 66. The optical display system of claim 40, wherein the stereoscopic image includes far field elements, wherein a far field element is an element intended for observation $> 2\text{m}$ away from a viewer, wherein the holographic image

media includes near field 3D objects, wherein a near field object is an object intended for observation < 2m from the viewer.

67. The optical display system of claim 40, wherein the stereoscopic image and the holographic image comprise at least one of a two-dimensional (2D) image, a two-dimensional (2D) representation, two-dimensional (2D) information, a three-dimensional (3D) object or a three-dimensional (3D) scene.

68. The optical display system of claim 40, wherein the light modulating elements of the array of light modulating elements is configured to modulate at least one of amplitude, phase or polarization.

69. A method for execution in a display device, the method comprises:

receiving data representative of media for display;

rendering, based on the data, a stereoscopic image;

rendering, based on the data, a holographic image;

combining, using one or more optical elements, the stereoscopic image and the holographic image to present a viewable combined image for a viewer.

70. The method of claim 69, wherein the data representative of media for display comprises background elements and foreground elements, with one or more background elements adapted for display in the stereoscopic image and the foreground elements adapted for display in the holographic image.

71. The method of claim 69, wherein media for display within a foveated area is displayed as one or more holographic images and media for display outside the foveated area is displayed as one or more stereoscopic images.

72. An optical display system, comprising

a stereoscopic display; and

one or more spatial light modulators configured to display one or more holographic objects.

73. The optical display system of claim 72, wherein the stereoscopic display is implemented with one or more spatial light modulators.

74. The optical display system of claim 73, wherein the one or more spatial light modulators are implemented as Liquid Crystal on Silicon (LCoS) spatial light modulators.

75. The optical display system of claim 72, wherein each of the one or more spatial light modulators configured to display one or more holographic objects comprise an array of unit cells, each unit cell configured to be individually addressable and further configured to control modulation of light incident to the spatial light modulator, wherein the center-to-center distance between two adjacent unit cells is less than a wavelength of visible light.

76. The optical display system of claim 72, wherein the spatial light modulators forming the stereoscopic display and the one or more spatial light modulators configured to display one or more holographic objects are illuminated by an illumination source having a same illumination spectrum.

5 77. The optical display system of claim 72, wherein the one or more illumination sources are configured to provide red, green, blue (RGB) light.

78. The optical display system of claim 72, further comprising a x-cube beam splitter configured to illuminate the stereoscopic display and the one or more light modulating elements configured to display a holographic image.

10

79. The optical display system of claim 72, the one or more arrays of light modulating elements having a respective top surface and a respective bottom surface, wherein a quarter wave plate is adapted over the top surface of the one or more arrays of light modulating elements.

15 80. The optical display system of claim 72, wherein the one or more optical elements include one or more polarizing beam splitters.

81. The optical display system of claim 72, wherein the one or more display elements configured as a stereoscopic display include one or more transmissive liquid crystal displays.

20

82. The optical display system of claim 81, the one or more transmissive liquid crystal displays having a respective top surface and a respective bottom surface, wherein a polarizing filter is formed over the bottom surface of the one or more transmissive liquid crystal displays.

25 83. The optical display system of claim 72, the one or more transmissive liquid crystal displays having a respective top surface and a respective bottom surface, wherein a polarizing filter is formed over the top surface of the one or more transmissive liquid crystal displays.

30 84. The optical display system of claim 72, the one or more transmissive liquid crystal displays having a respective top surface and a respective bottom surface, wherein a first polarizing filter is formed over the top surface of the one or more transmissive liquid crystal displays and a second polarizing filter is formed over the bottom surface of the liquid crystal display, wherein a polarization axis of the first polarizing filter is orthogonal to a polarization axis of the second polarizing filter.

35 85. The optical display system of claim 72, wherein the one or more transmissive liquid crystal displays further comprising one or more illumination sources configured to provide backside illumination for the one or more transmissive liquid crystal displays.

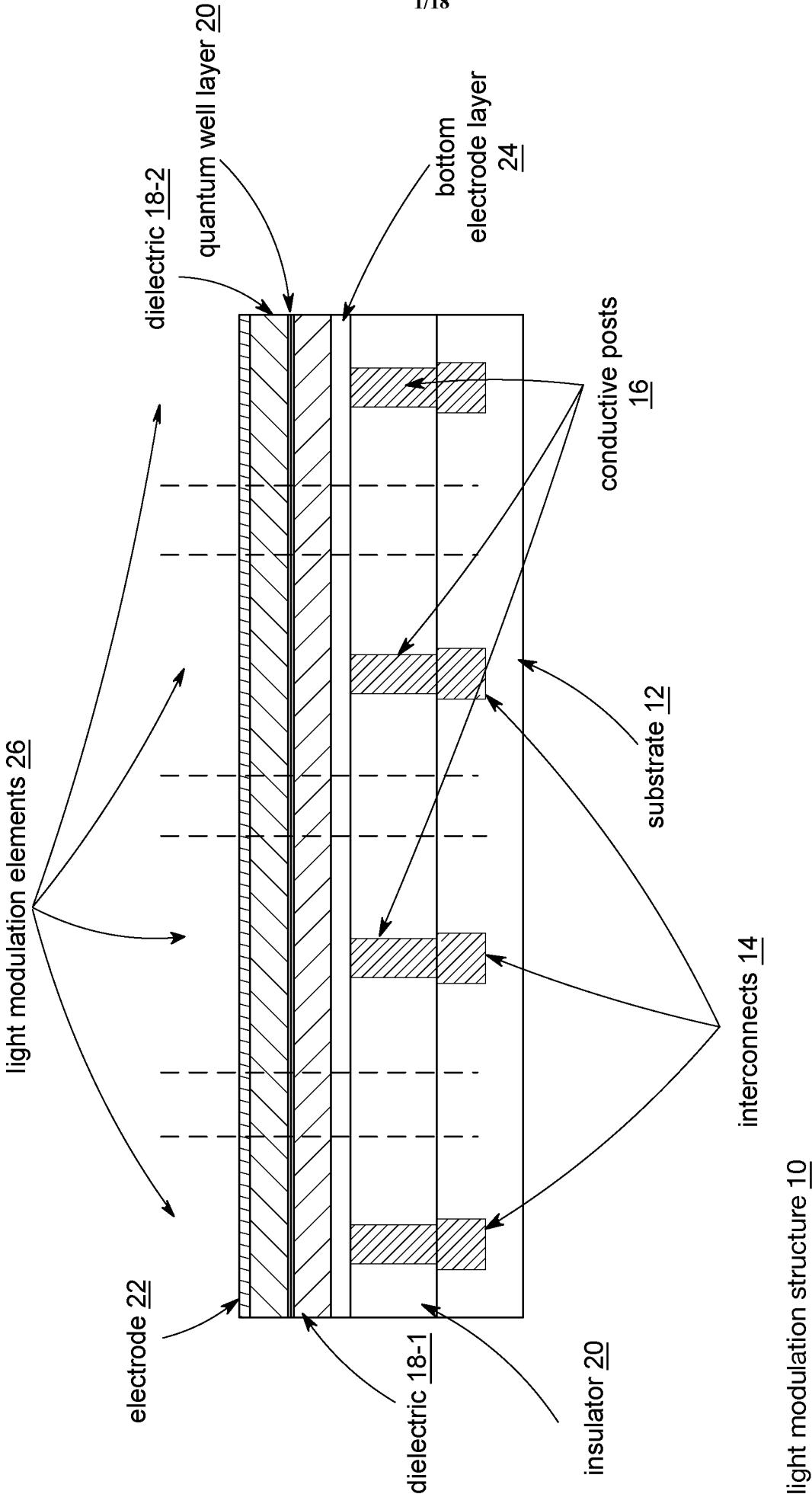


FIG. 1A

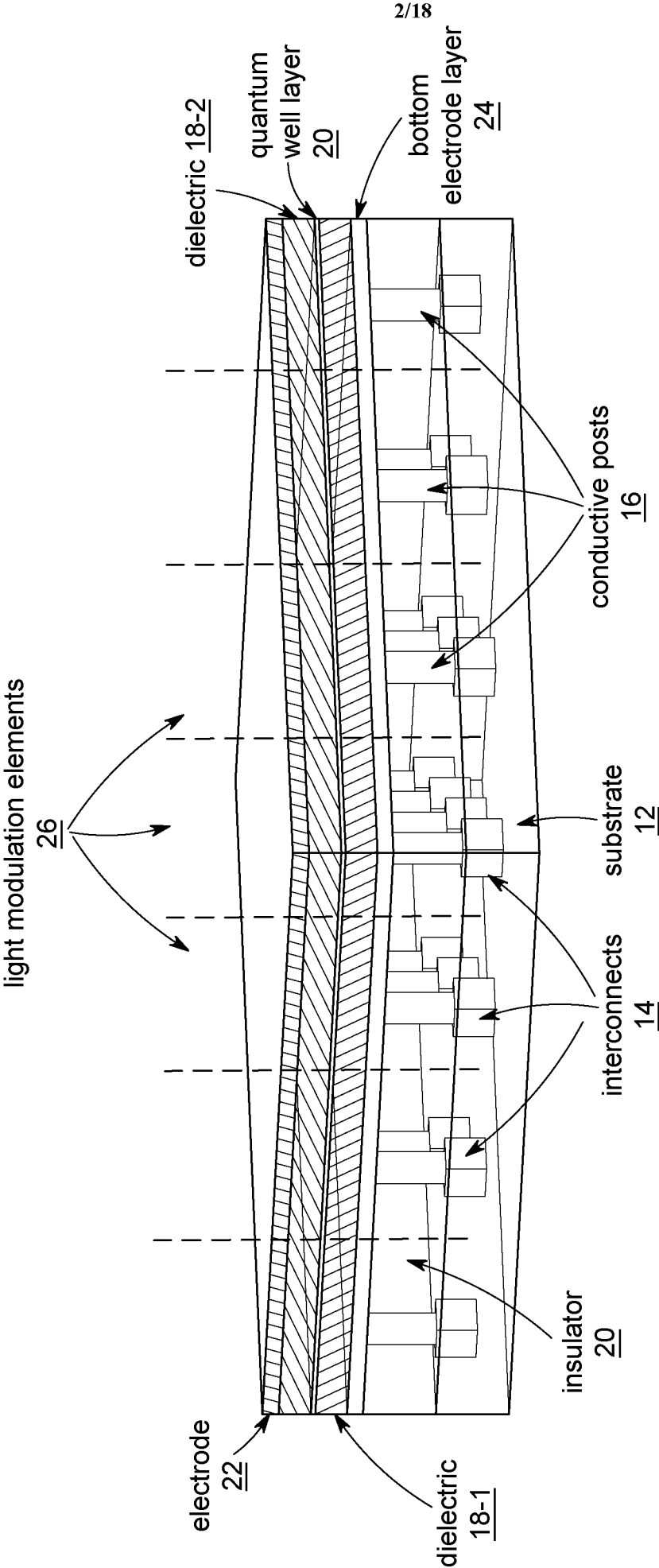


FIG. 1B

light modulation structure 10

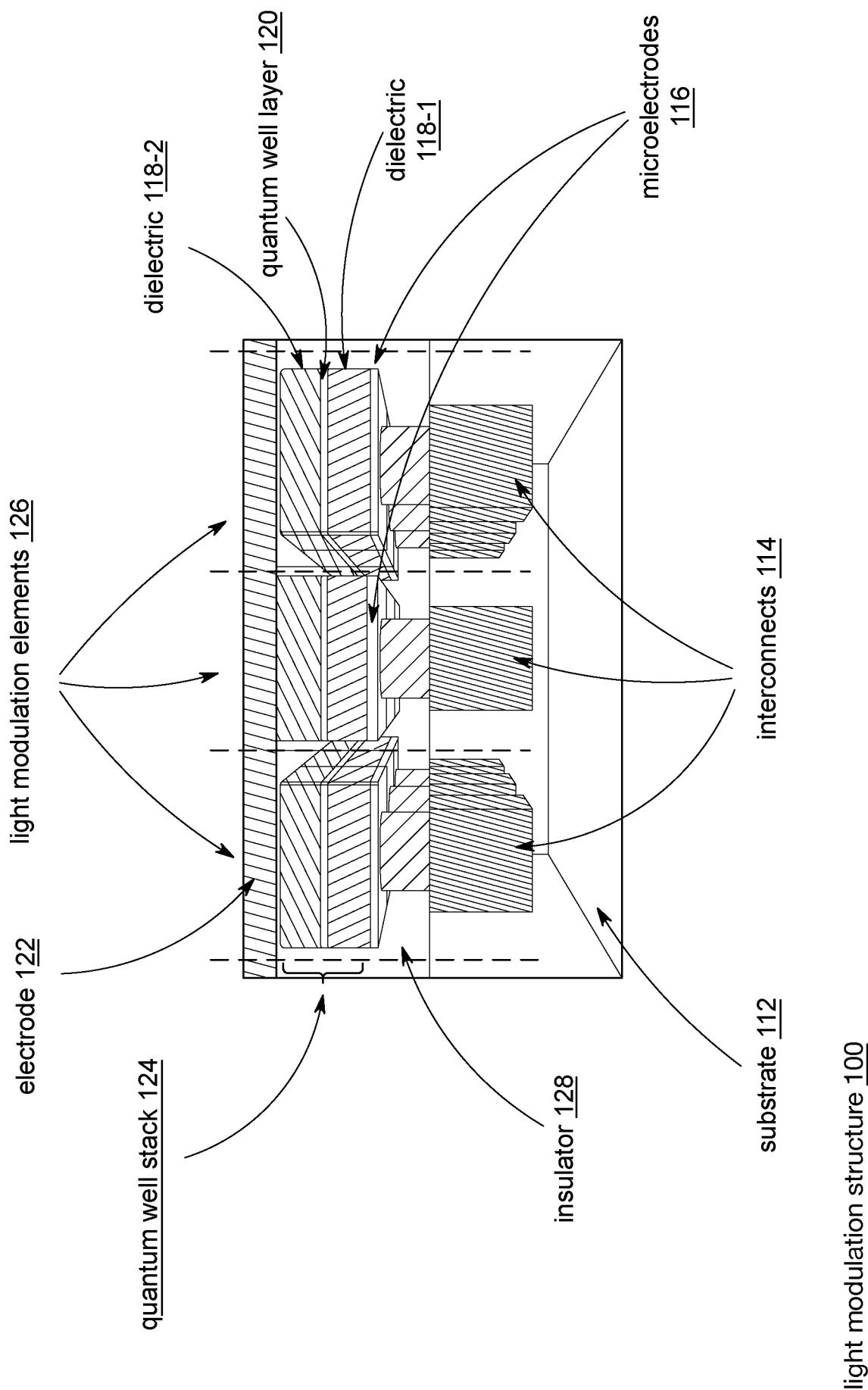
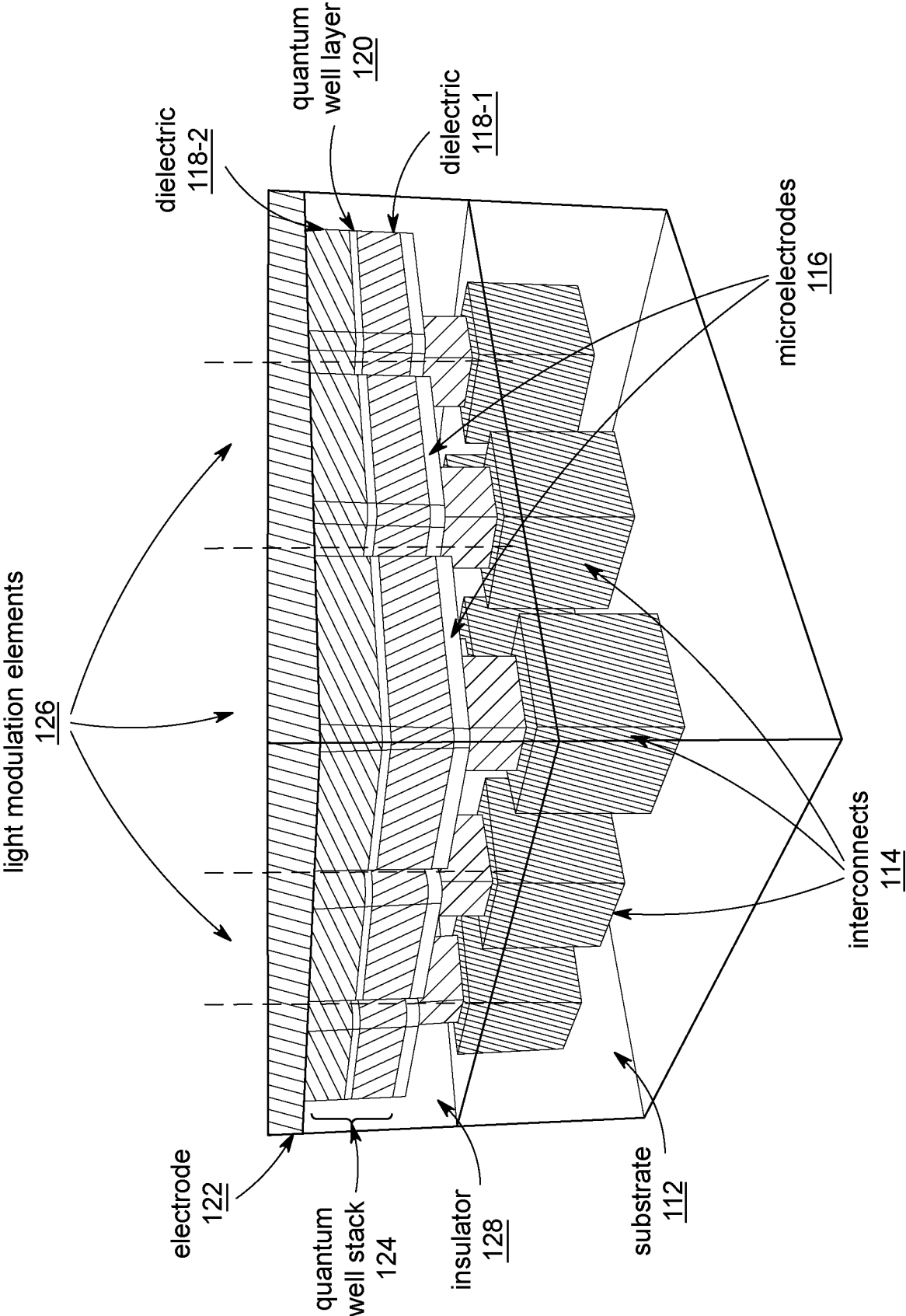


FIG. 2A



light modulation structure 100

FIG. 2B

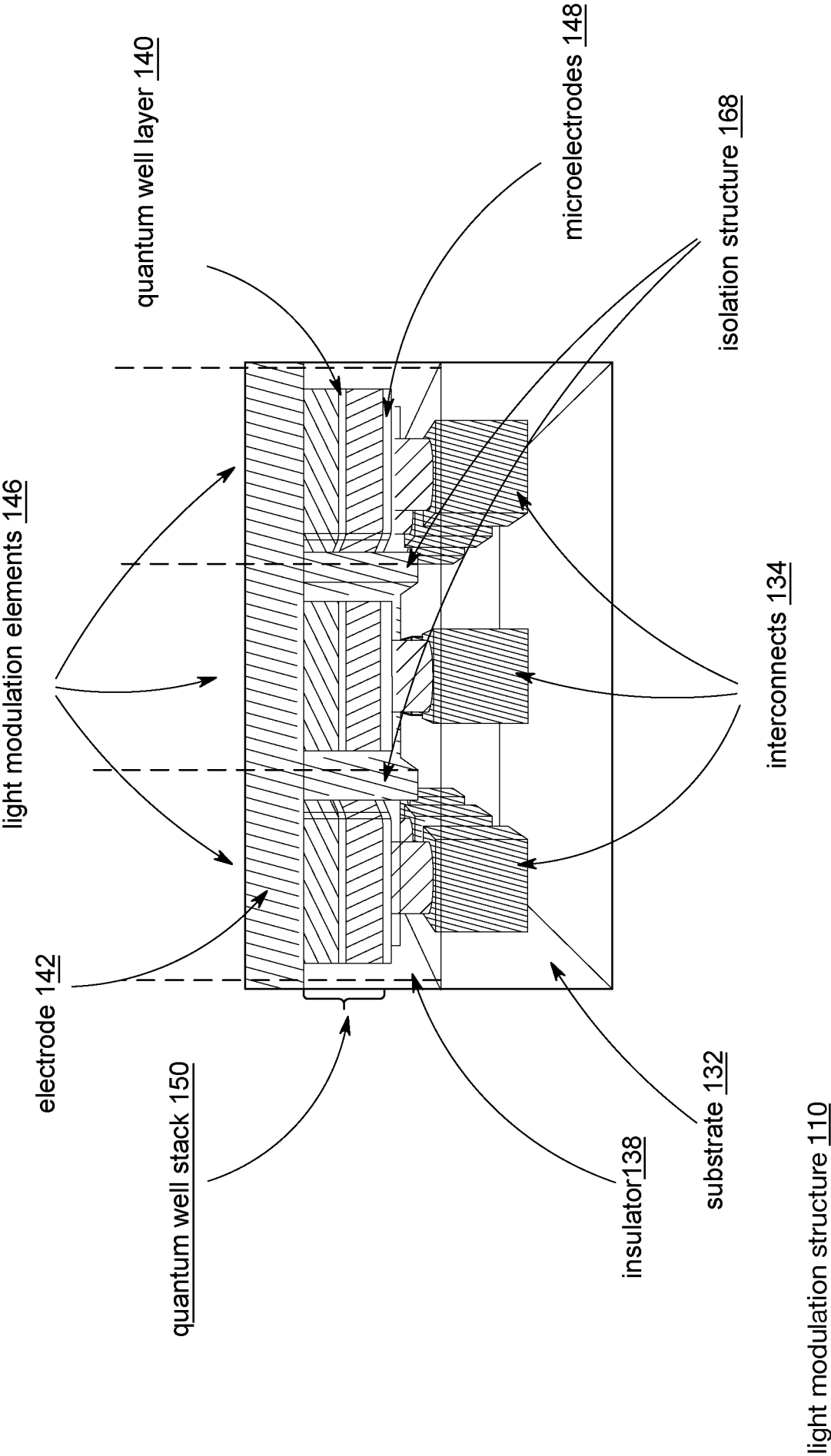
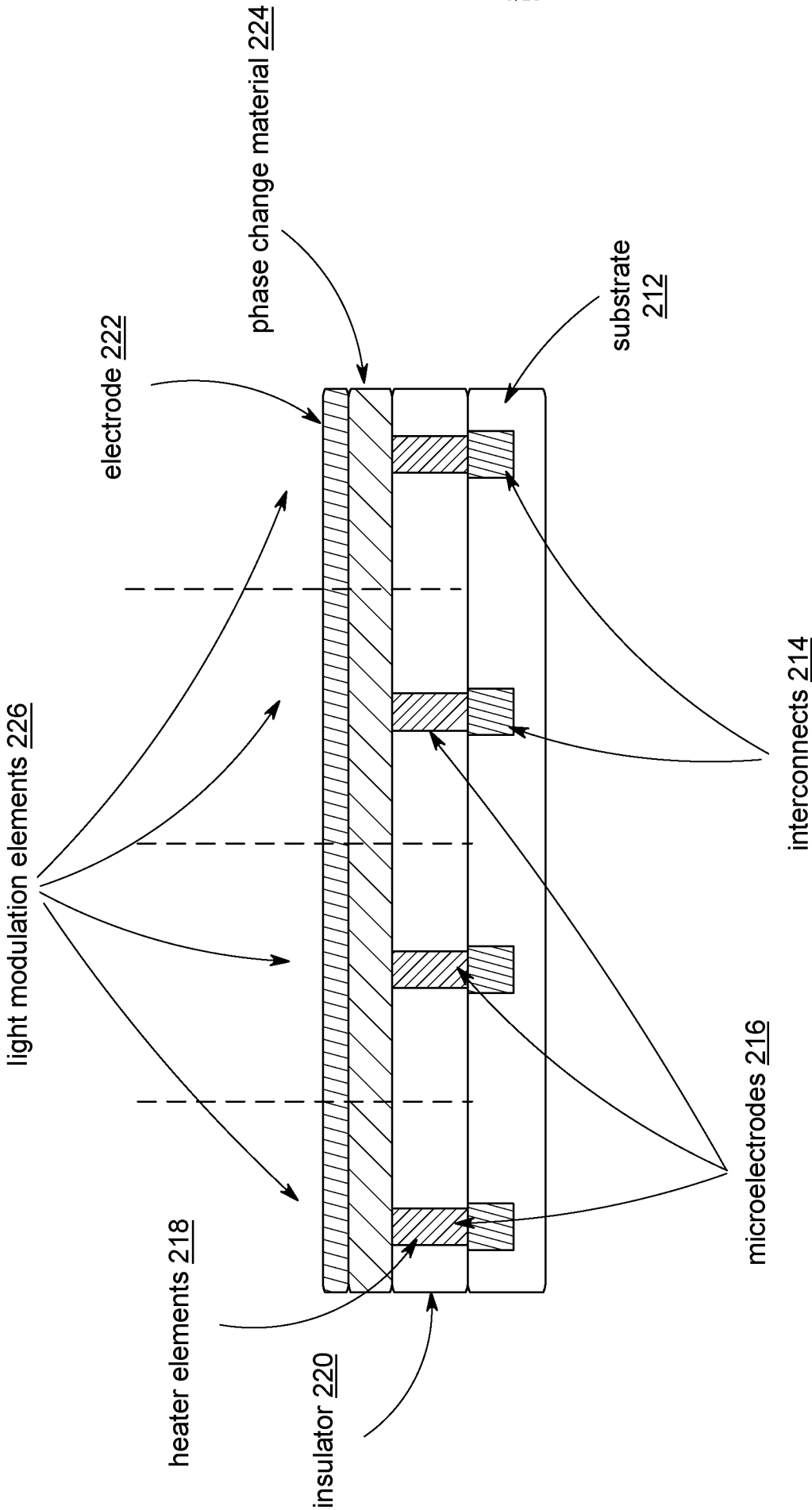
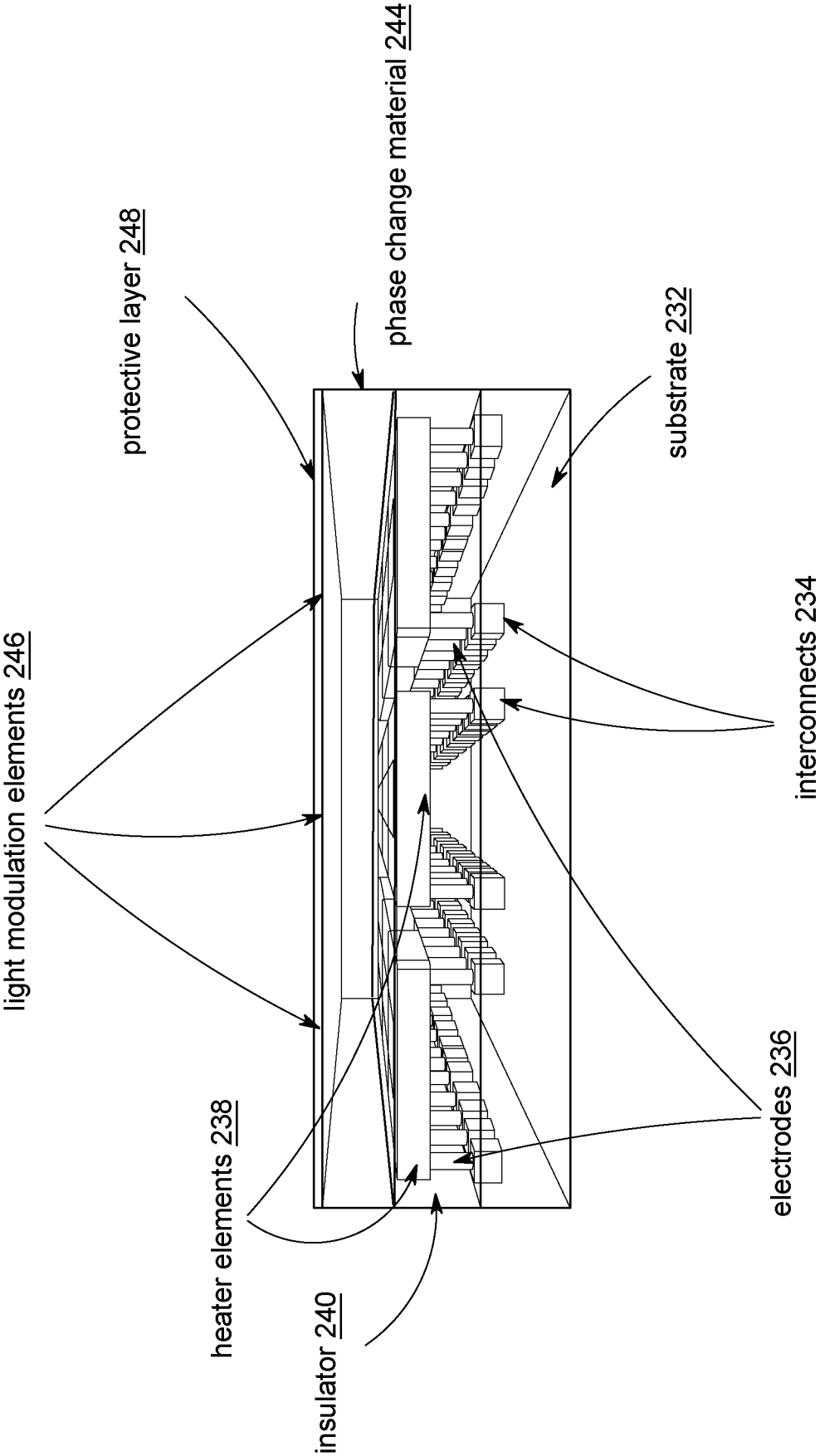


FIG. 2C





light modulation structure 300

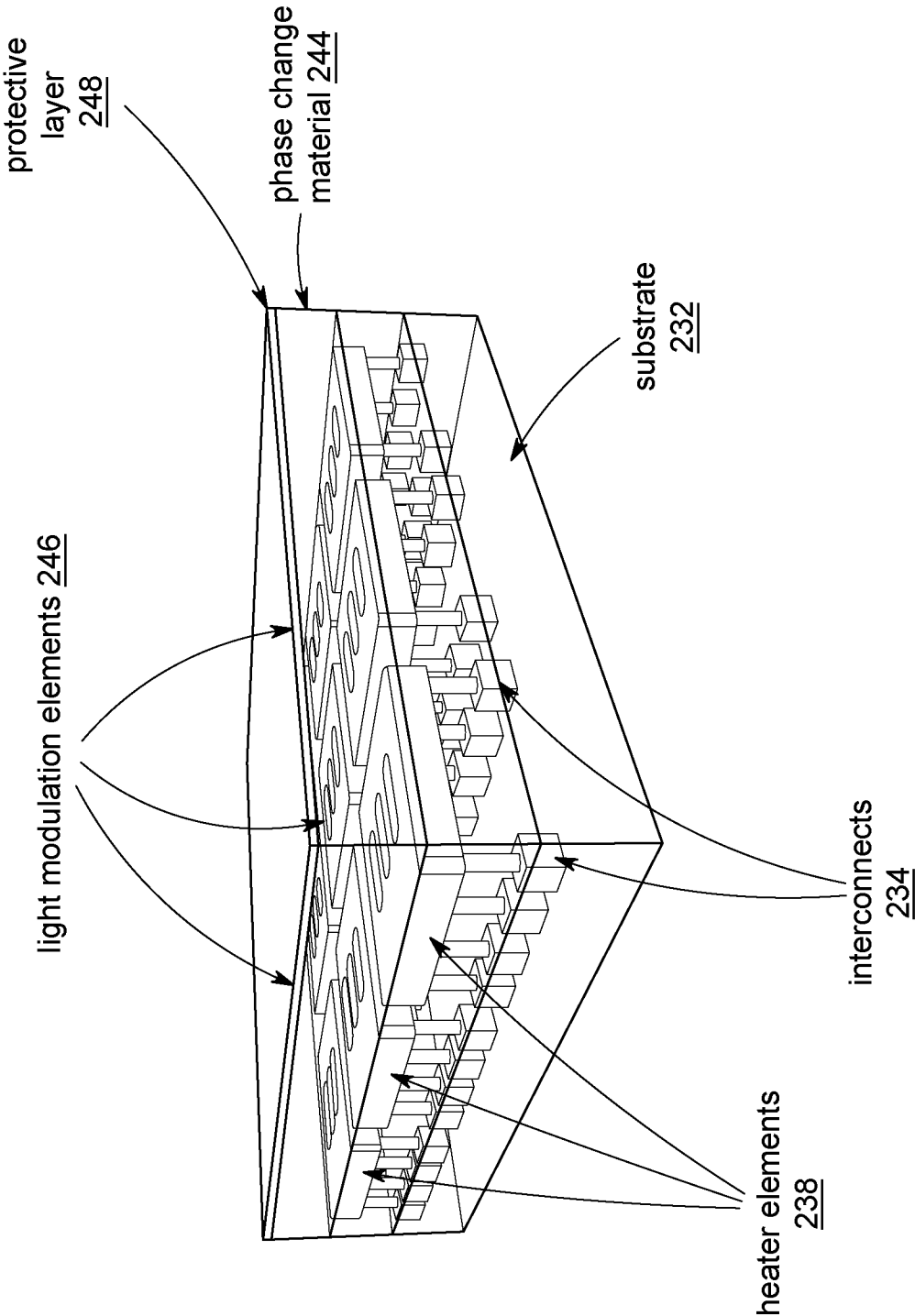


FIG. 4B

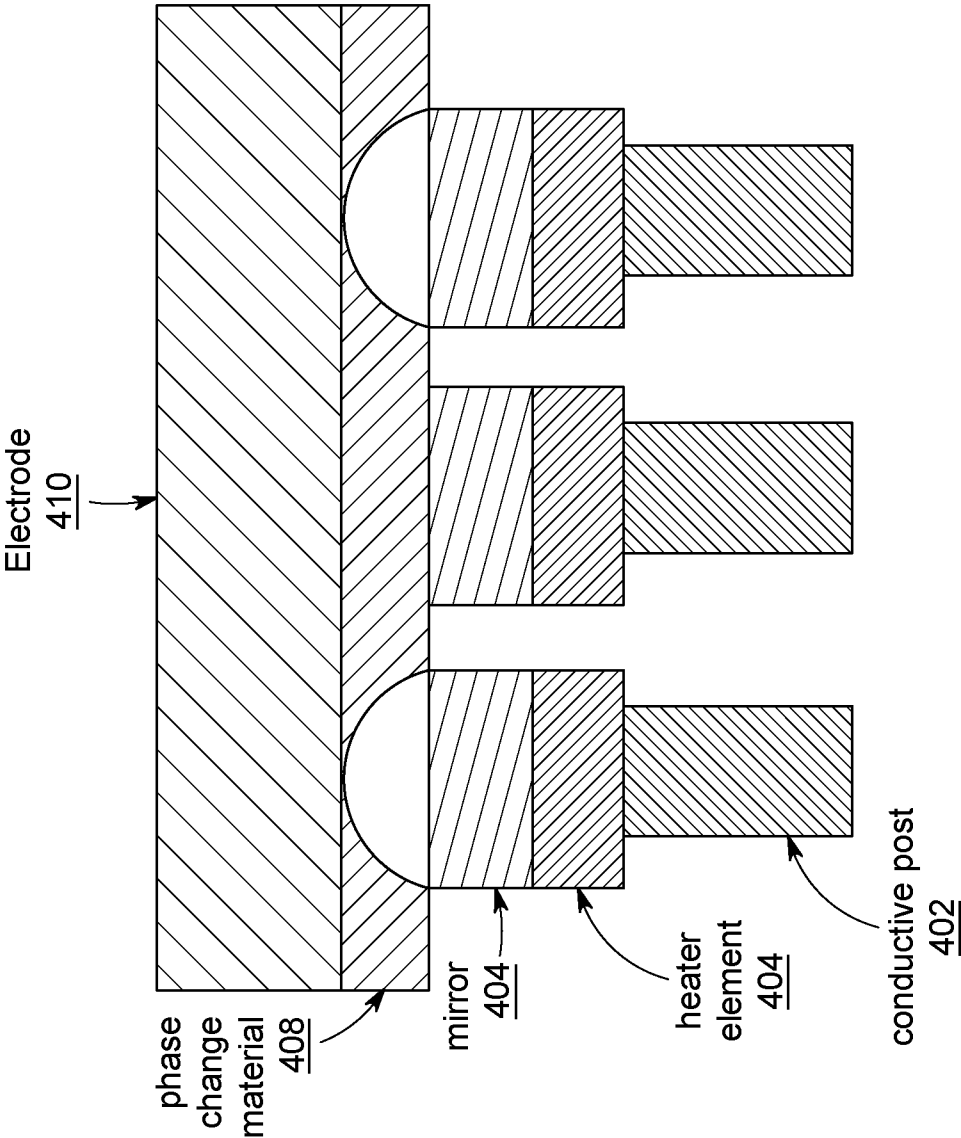
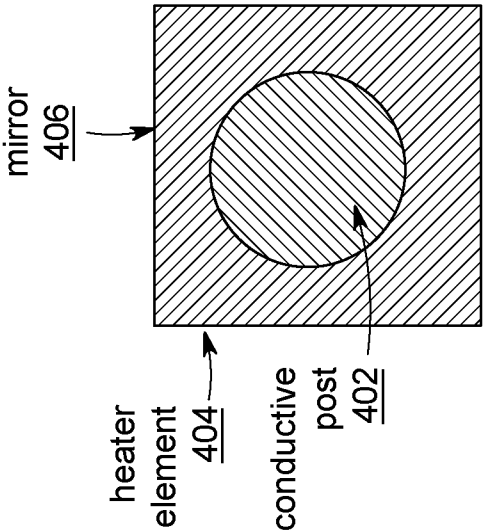


FIG. 5A

light modulation structure 400



light modulation structure 400

light modulation structure 400

FIG. 5B

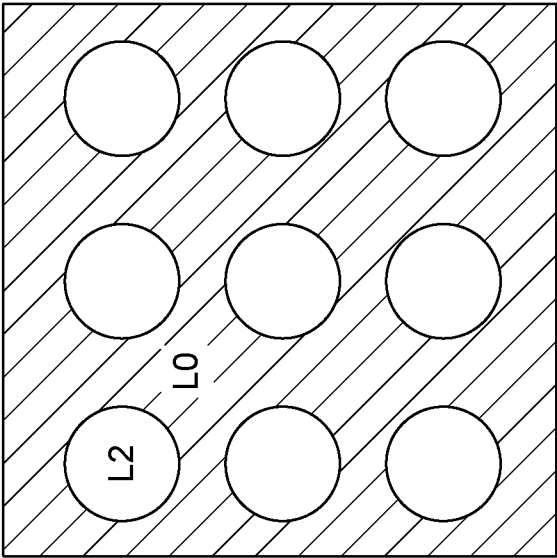


FIG. 6A

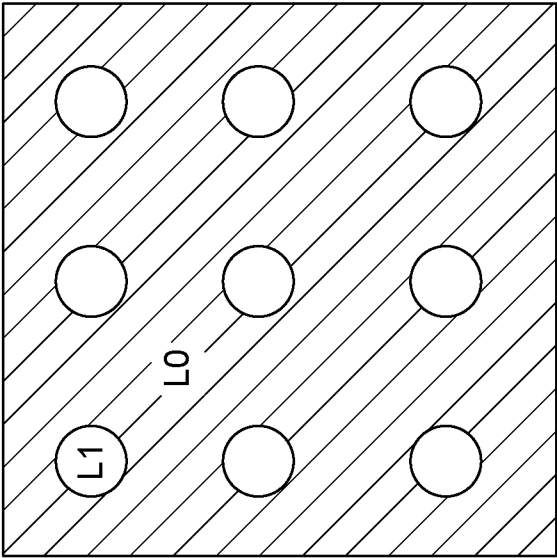


FIG. 6B

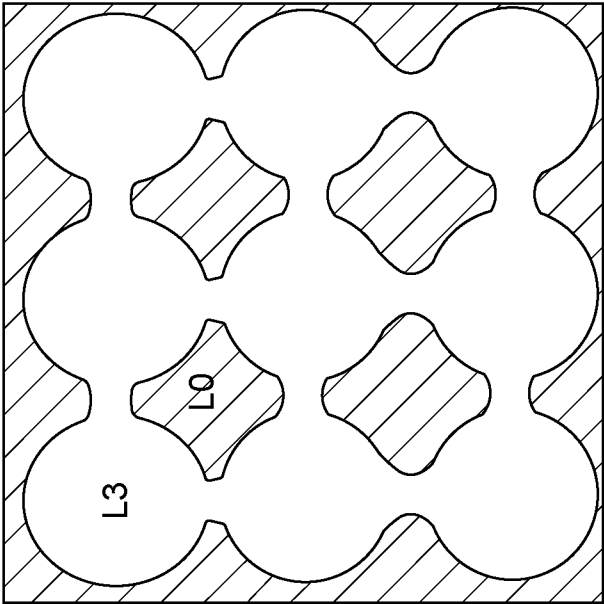
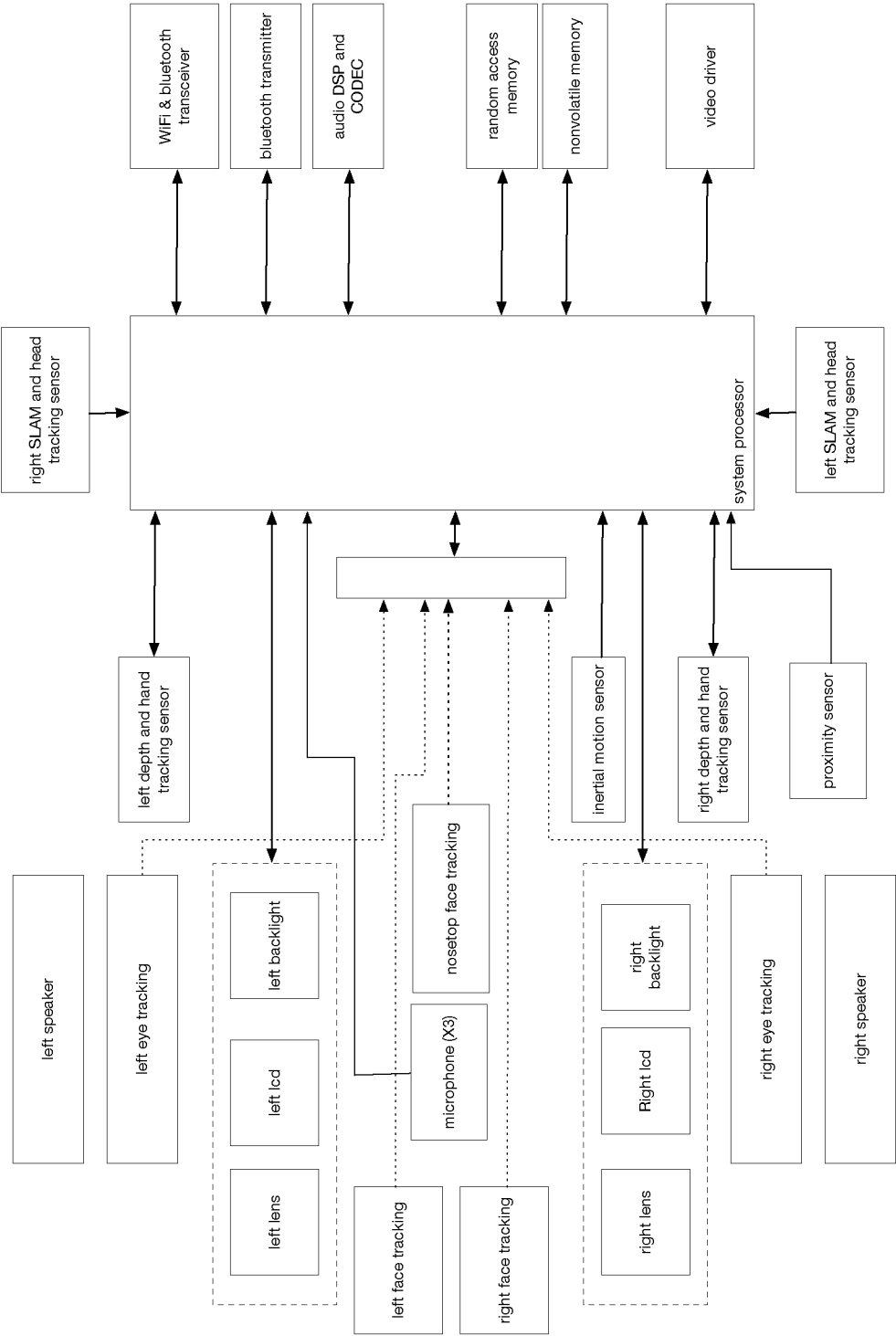


FIG. 6C



virtual reality system 10

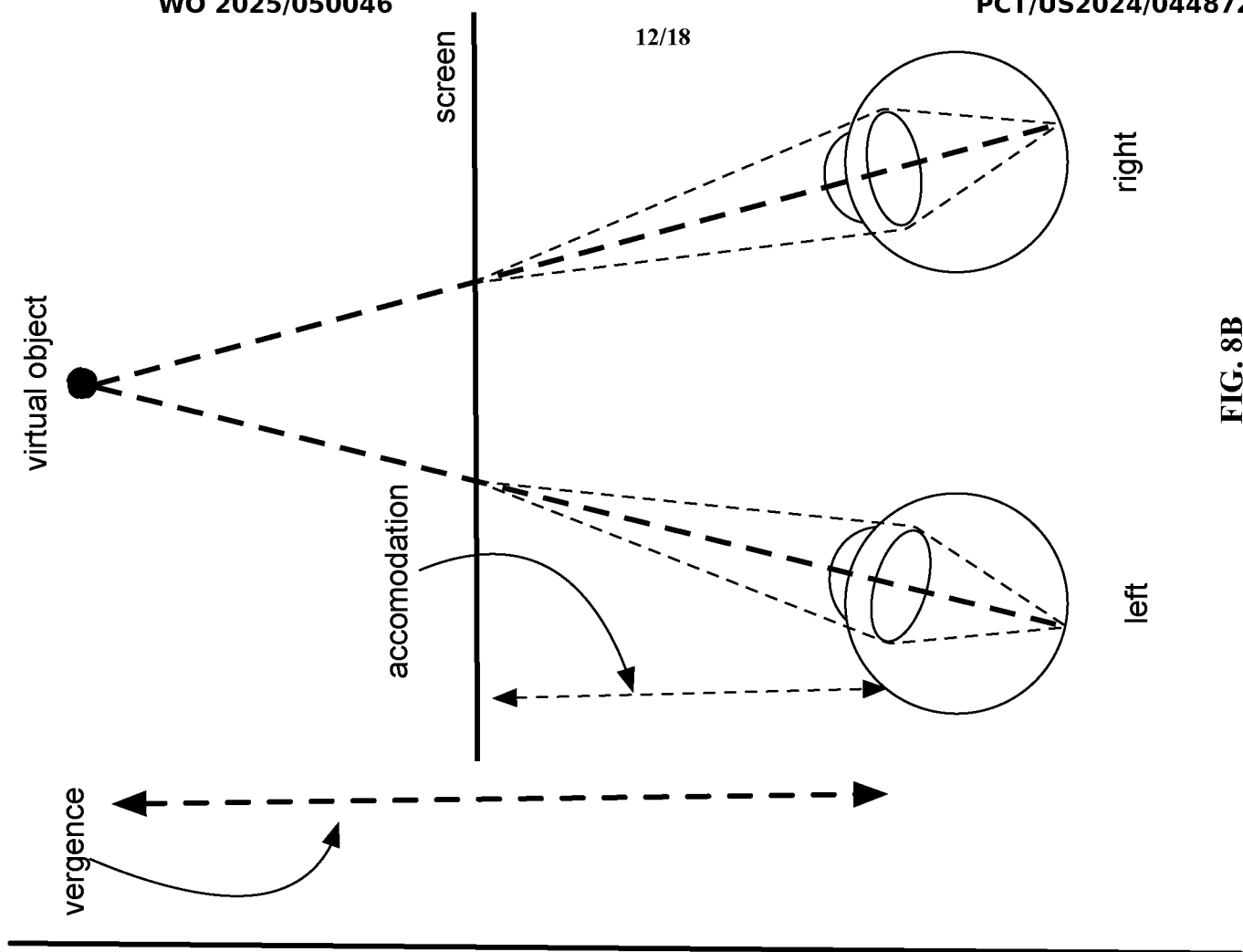


FIG. 8B

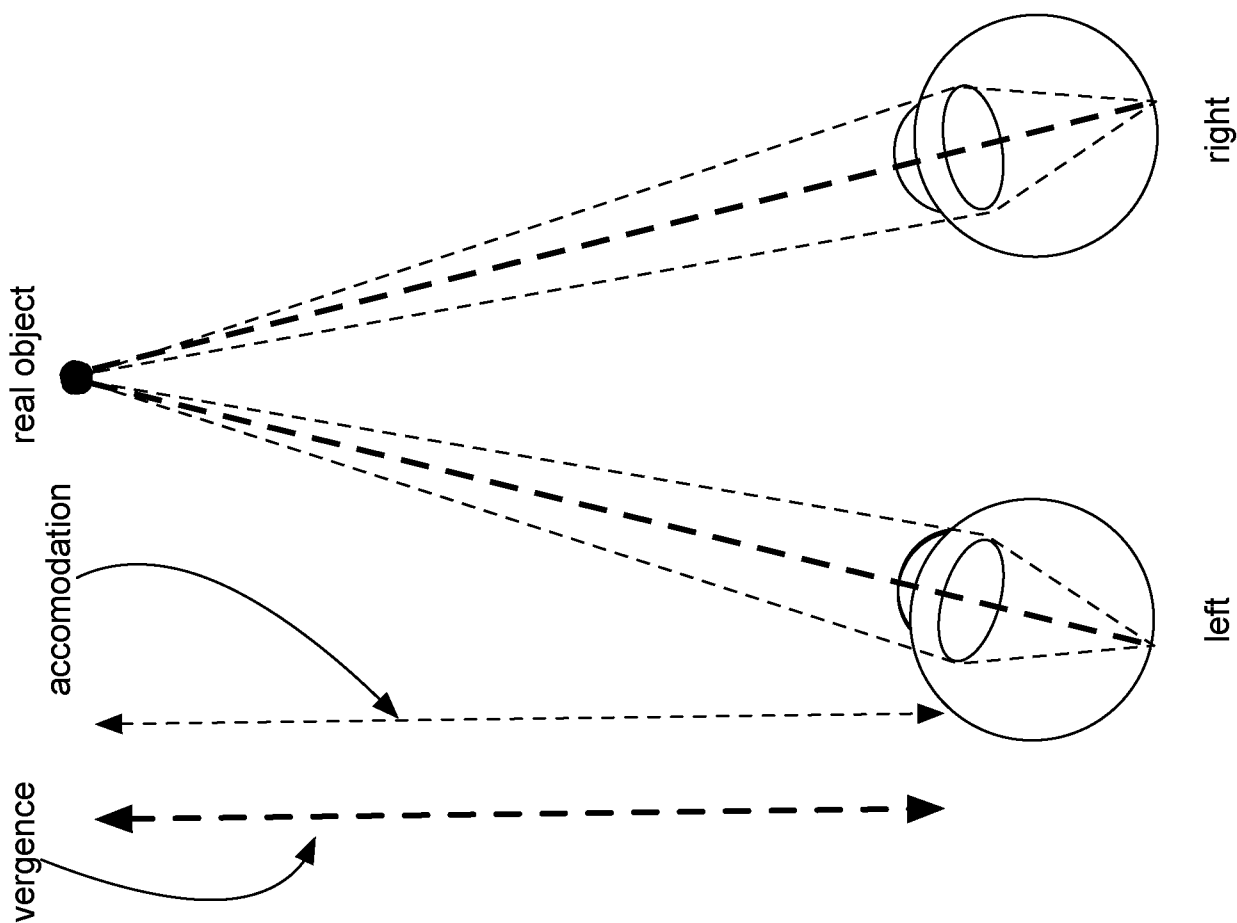


FIG. 8A

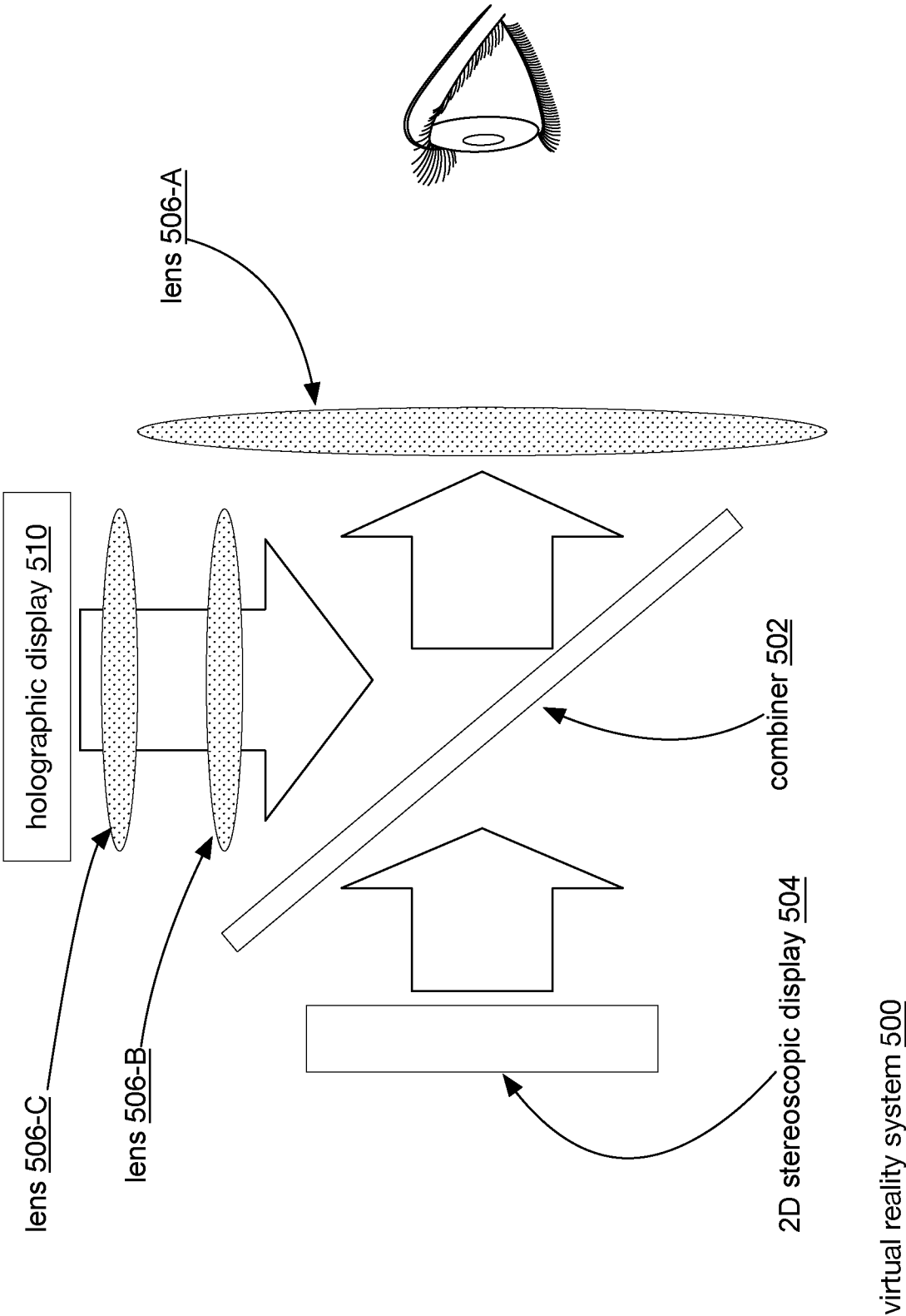
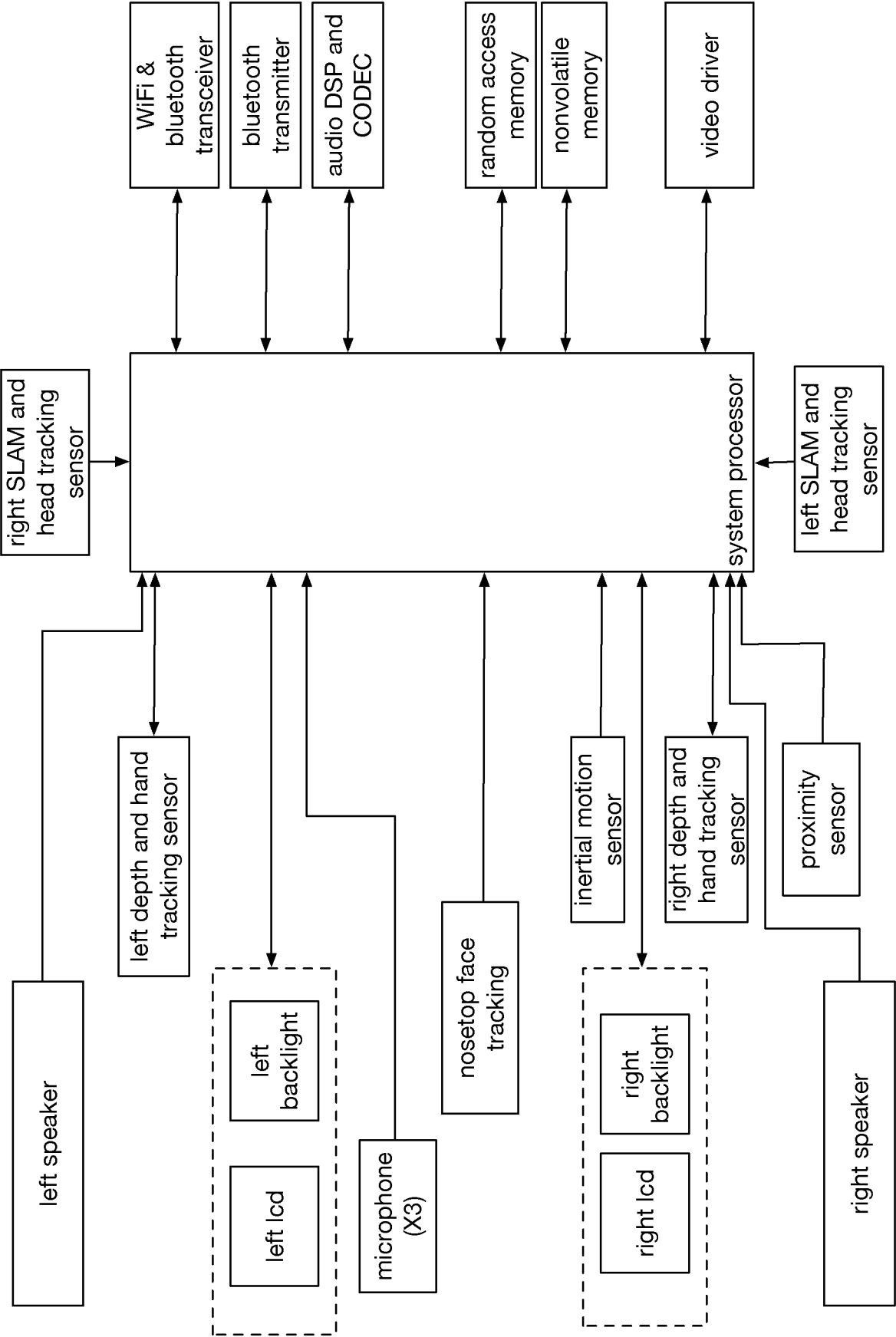


FIG. 9A



virtual reality system 20

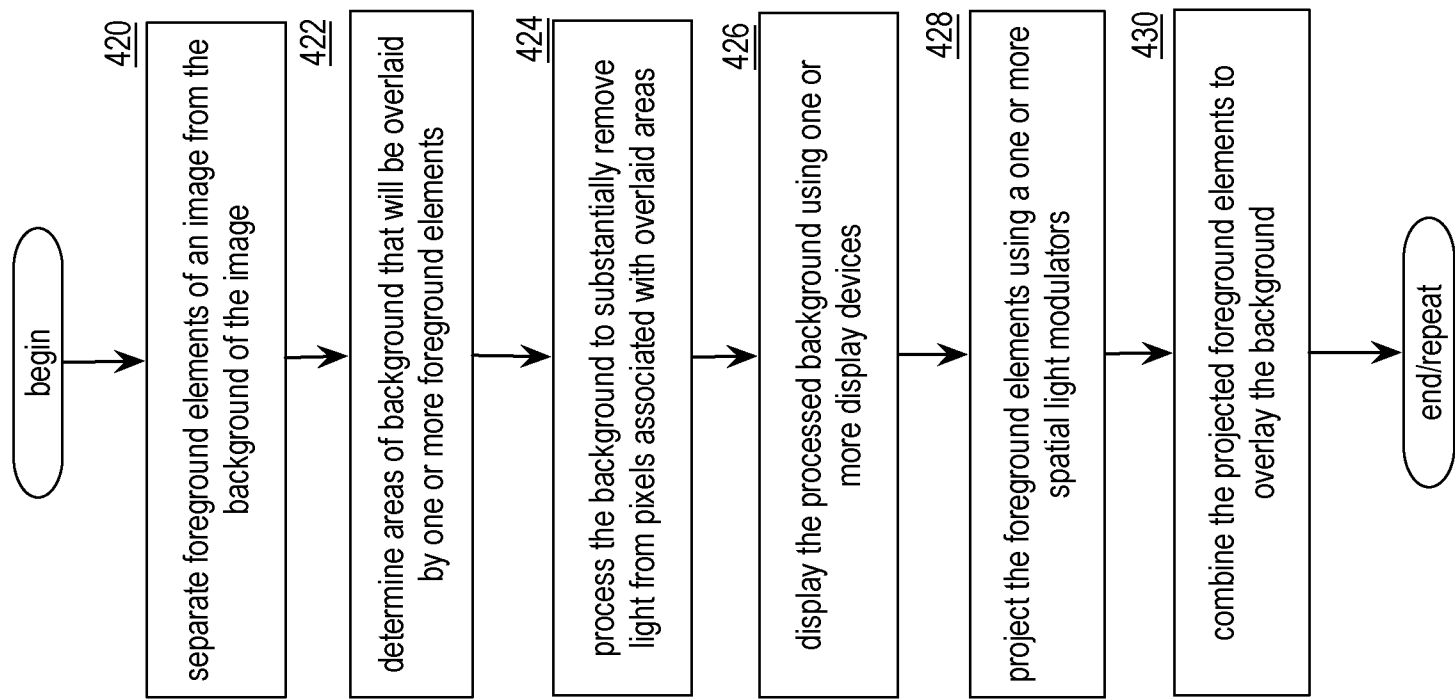
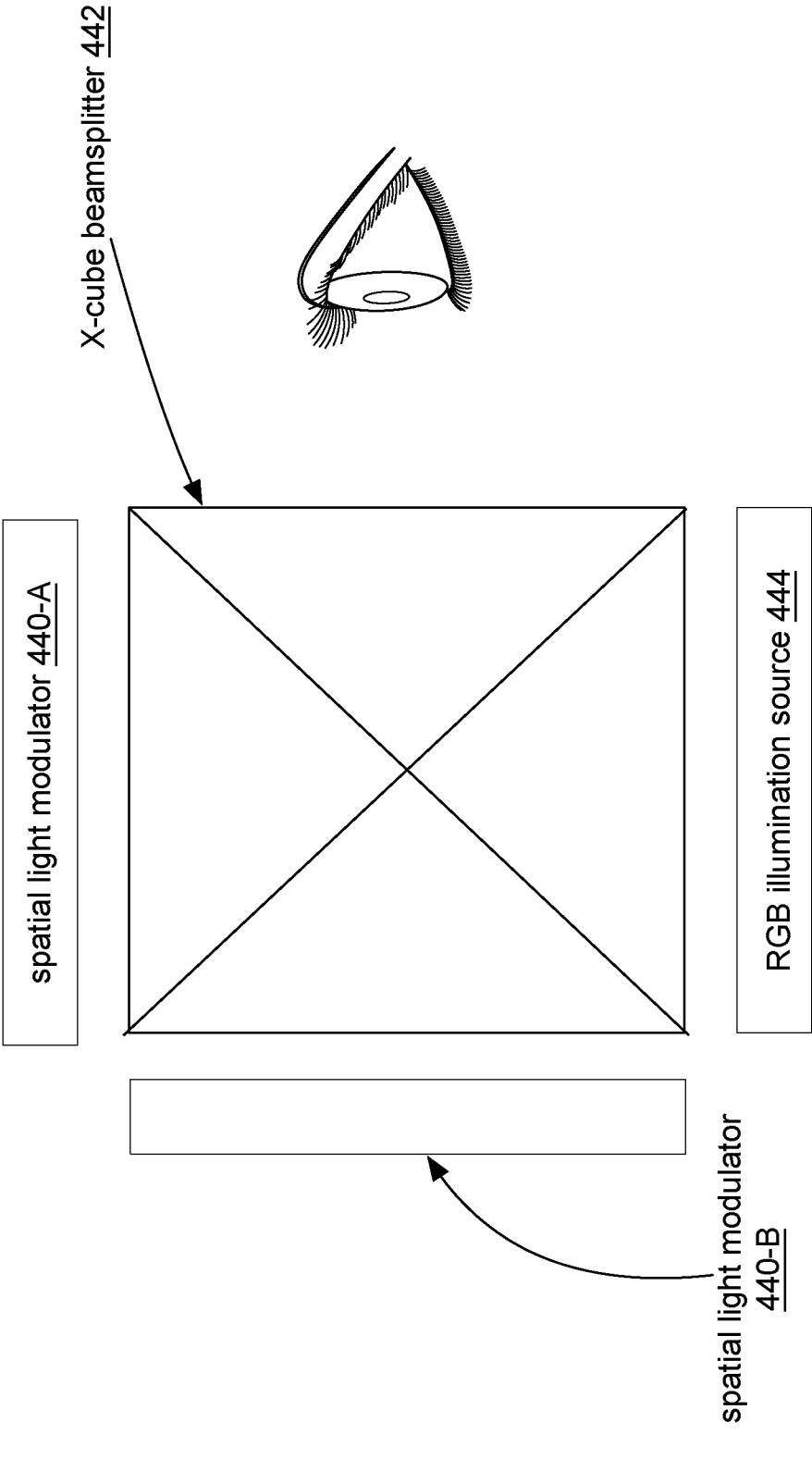


FIG. 9C



virtual reality system 550

FIG. 10

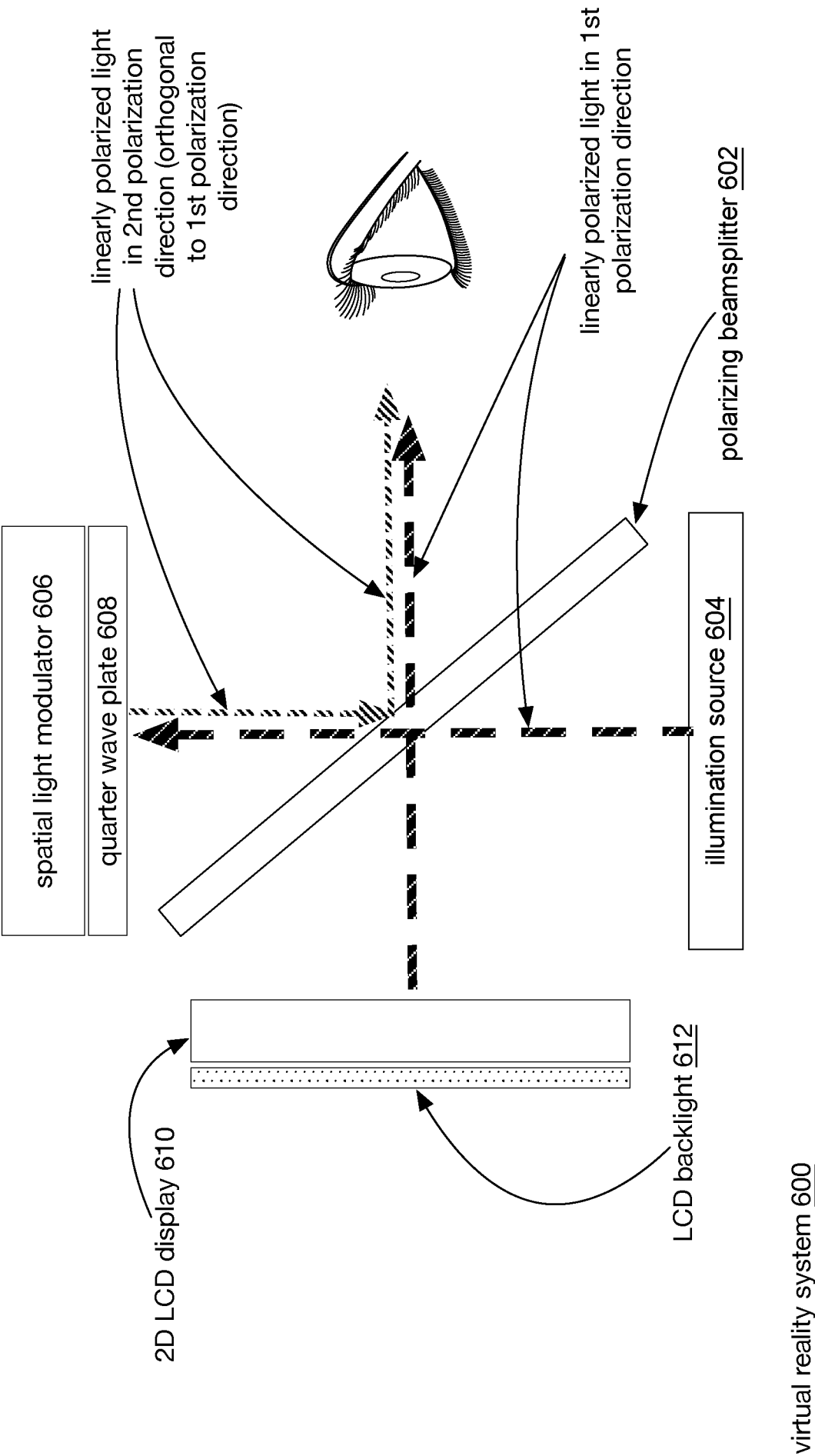
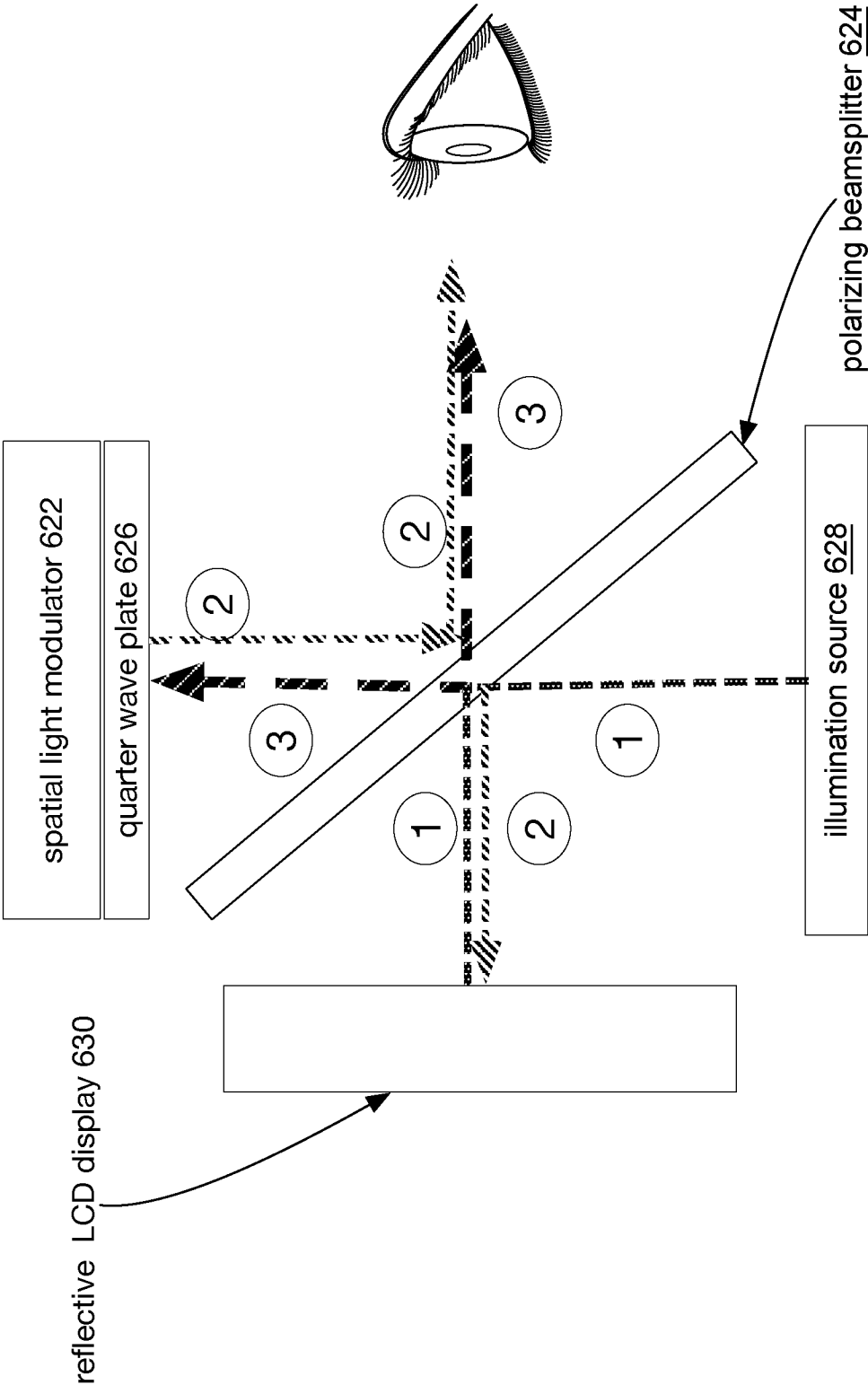


FIG. 11



virtual reality system 620

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/044872

A. CLASSIFICATION OF SUBJECT MATTER

G02F 1/017(2006.01)i; **G02F 1/00**(2006.01)i; **G03H 1/04**(2006.01)i; **G02F 1/1362**(2006.01)i; **G02B 27/28**(2006.01)i; **G02B 27/10**(2006.01)i; **G02B 27/02**(2006.01)i; **G02B 27/18**(2006.01)i; **G03H 1/02**(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02F 1/017(2006.01); G01S 17/02(2006.01); G01S 17/931(2020.01); G01S 7/481(2006.01); G02B 27/00(2006.01); G02B 27/01(2006.01); G02B 5/32(2006.01); G02F 1/00(2006.01); G02F 1/01(2006.01); G03H 1/16(2006.01); G03H 1/22(2006.01); G03H 1/26(2006.01); H04N 5/89(2006.01)

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

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: light modulating device, electrical interconnect, electrode, dielectric layer, quantum well, holographic, stereoscopic display, combine, object, background, color filter, light source, Computer-Generated Holography (CGH), LC(liquid crystal), splitter, polarizing filter, pupil

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2020-0284904 A1 (SAMSUNG ELECTRONICS CO., LTD.) 10 September 2020 (2020-09-10) paragraphs [0043], [0046]-[0047], [0053], [0055], [0058], [0064]-[0066], [0077]; and figures 1, 3A	1-15,18-39
Y	US 11314109 B1 (HRL LABORATORIES, LLC) 26 April 2022 (2022-04-26) column 7, lines 41-43; column 8, lines 24-32; column 8, line 51-52; column 8, line 66 – column 9, line 4; column 9, lines 27-33; column 10, lines 28-33; column 11, lines 34-37, 43-46; and figure 5	1-15,18-39
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Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance
“D” document cited by the applicant in the international application
“E” earlier application or patent but published on or after the international filing date
“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
“O” document referring to an oral disclosure, use, exhibition or other means
“P” document published prior to the international filing date but later than the priority date claimed

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

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

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

“&” document member of the same patent family

Date of the actual completion of the international search

12 February 2025

Date of mailing of the international search report

12 February 2025

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/044872

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2020-0050147 A1 (DUALITAS LTD.) 13 February 2020 (2020-02-13) paragraphs [0023], [0063]-[0064]; claim 1; and figure 5	40-56,59-65, 67-74,76-83,85
Y	US 2012-0314021 A1 (PETER WAI MING TSANG) 13 December 2012 (2012-12-13) paragraphs [0052], [0092]; and figure 8	40-56,59-65, 67-74,76-83,85
Y	CN 110376739 A (ZHEJIANG UNIVERSITY) 25 October 2019 (2019-10-25) paragraphs [0036], [0038], [0042], [0051]; and figures 1-2	41,43-47,61,64- 65,79,82-83,85
Y	US 2021-0072701 A1 (SAMSUNG ELECTRONICS CO., LTD.) 11 March 2021 (2021-03-11) paragraphs [0066], [0071], [0075], [0077]-[0078], [0093], [0126]; and figures 1, 6, 18	42,44,47,50,53-56,60- 61,71,74,76-77,81-82
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Y	US 2019-0171005 A1 (SAMSUNG ELECTRONICS CO., LTD.) 06 June 2019 paragraphs [0070]-[0071], [0091], [0114]; and figures 1, 5, 14	49,52,62-63,67,70,78
A	US 2012-0019883 A1 (BYUNG GYU CHAE et al.) 26 January 2012 paragraphs [0040]-[0047]; and figures 1A-1B	1-85

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/044872

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

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

Group I: Claims 1-39 directed to a structure of a light modulating device.

Group II: Claims 40-85 directed to a configuration of an optical display system and a method for execution in a display device.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

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

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/US2024/044872

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2024/044872

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