US 20210055551A1

(19) **United States**

(12) **Patent Application Publication**

Chi et al.

(10) **Pub. No.: US 2021/0055551 A1**

(43) **Pub. Date: Feb. 25, 2021**

(54) **DISPERSION COMPENSATION IN VOLUME BRAGG GRATING-BASED WAVEGUIDE DISPLAY**

(71) Applicant: **Facebook Technologies, LLC**, Menlo Park, CA (US)

(72) Inventors: **Wanli Chi**, Sammamish, WA (US); **Dominic Meiser**, Issaquah, WA (US); **Yang Yang**, Redmond, WA (US); **Wai Sze Tiffany Lam**, Redmond, WA (US); **Pasi Saarikko**, Kirkland, WA (US)

(21) Appl. No.: **16/681,530**

(22) Filed: **Nov. 12, 2019**

Related U.S. Application Data

(60) Provisional application No. 62/891,167, filed on Aug. 23, 2019.

Publication Classification

(51) **Int. Cl.**

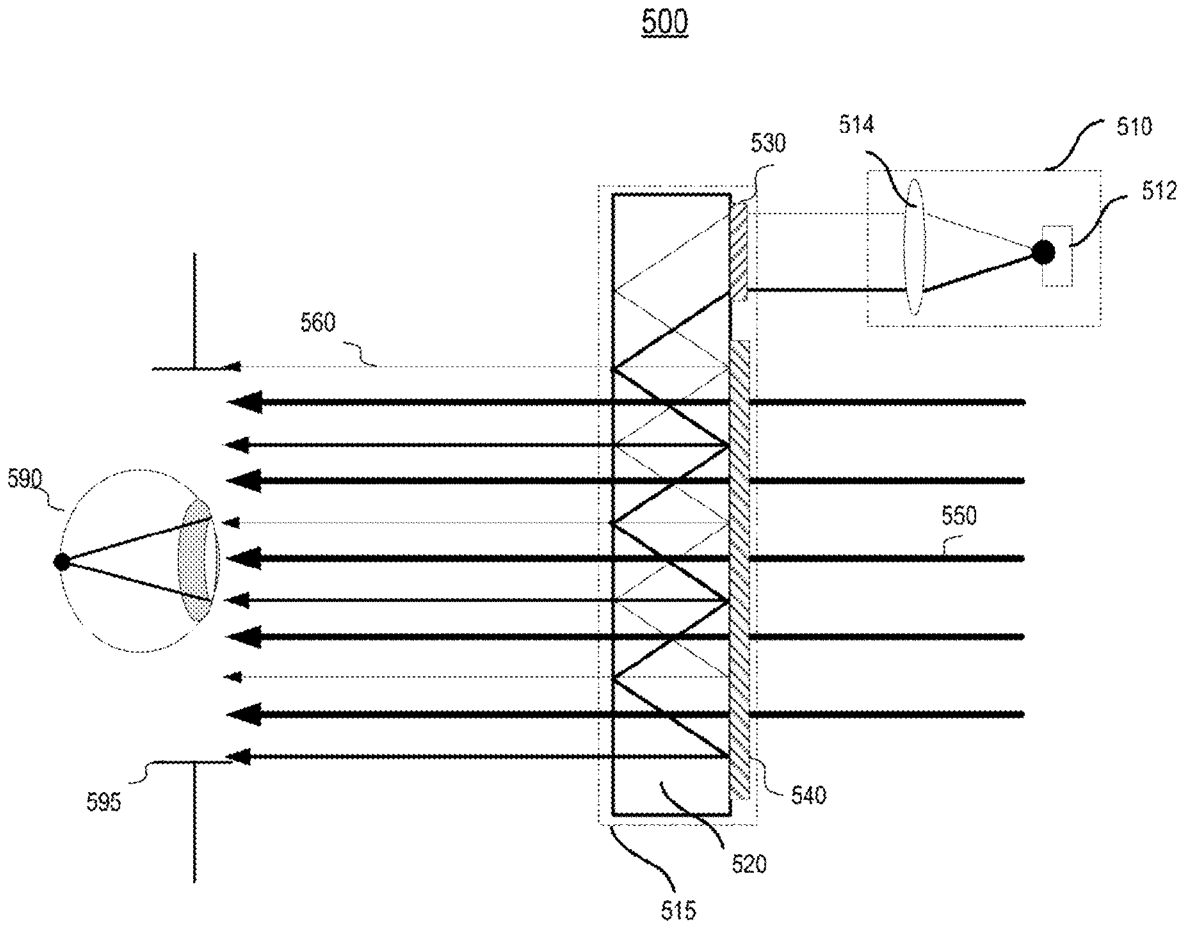
G02B 27/01	(2006.01)
G02B 27/42	(2006.01)
G02B 1/11	(2006.01)
F21V 8/00	(2006.01)

(52) **U.S. Cl.**

CPC ***G02B 27/0172*** (2013.01); ***G02B 27/4205*** (2013.01); ***G02B 1/11*** (2013.01); ***G02B 6/0026*** (2013.01); ***G02B 6/005*** (2013.01); *G02B 27/0081* (2013.01); *G02B 2027/0174* (2013.01); *G02B 2027/0118* (2013.01); *G02B 2027/0123* (2013.01); *G02B 2027/0138* (2013.01); *G02B 2027/0112* (2013.01); *G02B 2027/0178* (2013.01)

(57) **ABSTRACT**

A waveguide display includes a substrate transparent to visible light, a coupler configured to couple display light into the substrate as guided wave in the substrate, and a first VBG and a second VBG coupled to the substrate. The coupler includes a diffractive coupler, a refractive coupler, or a reflective coupler. The first VBG is configured to diffract, at a first region of the first VBG, the display light in the substrate to a first direction, and diffract, at two or more regions of the first VBG along the first direction, the display light from the first region to a second direction towards the second VBG. The second VBG is configured to couple the display light from each of the two or more regions of the first VBG out of the substrate at two or more regions of the second VBG along the second direction.



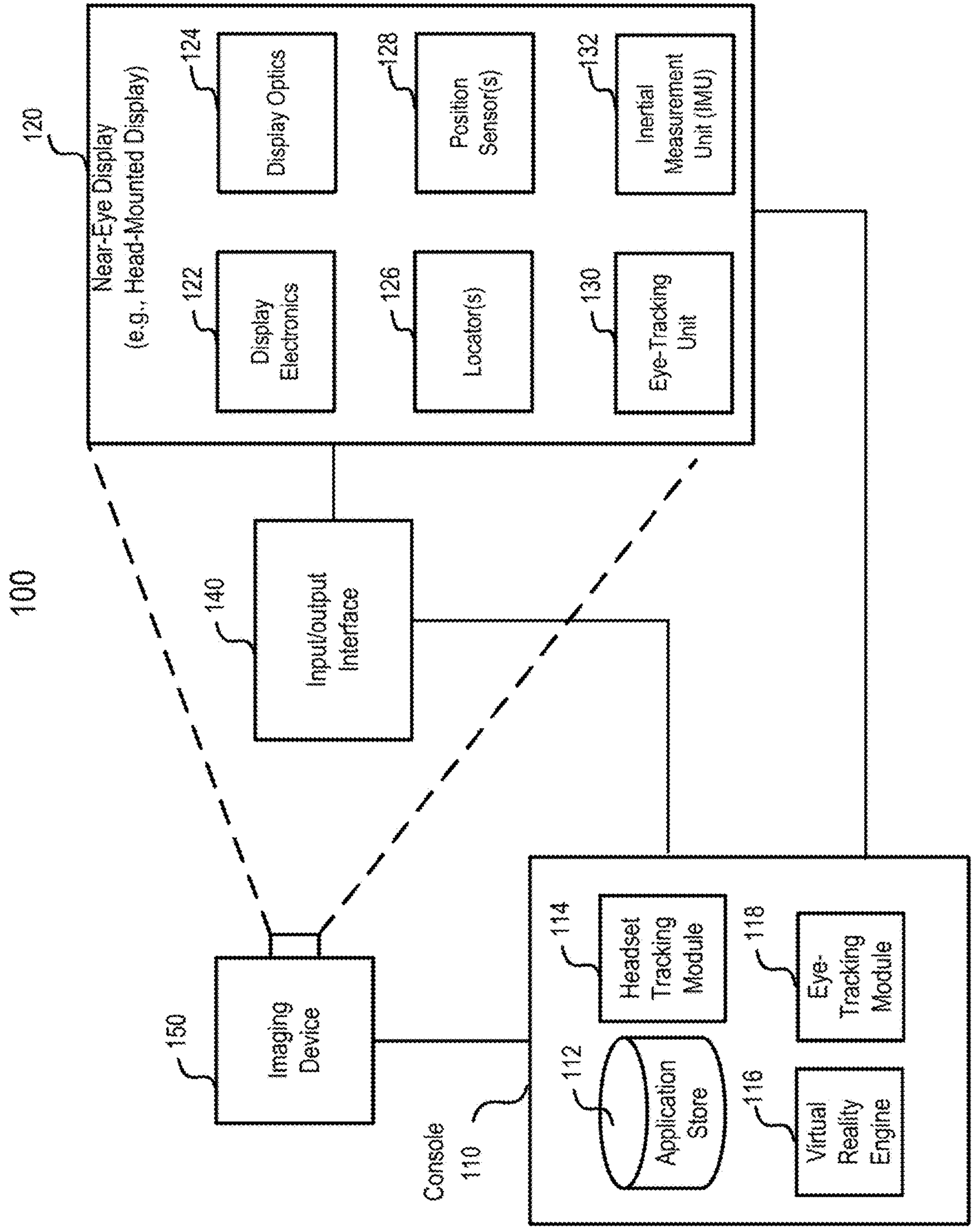

100
120
Near-Eye Display
(e.g., Head-Mounted Display)
122
Display Electronics
124
Display Optics
126
Locator(s)
128
Position Sensor(s)
130
Eye-Tracking Unit
132
Inertial Measurement Unit (IMU)
140
Input/output Interface
150
Imaging Device
Console
110
112
Application Store
114
Headset Tracking Module
116
Virtual Reality Engine
118
Eye-Tracking Module

FIG. 1

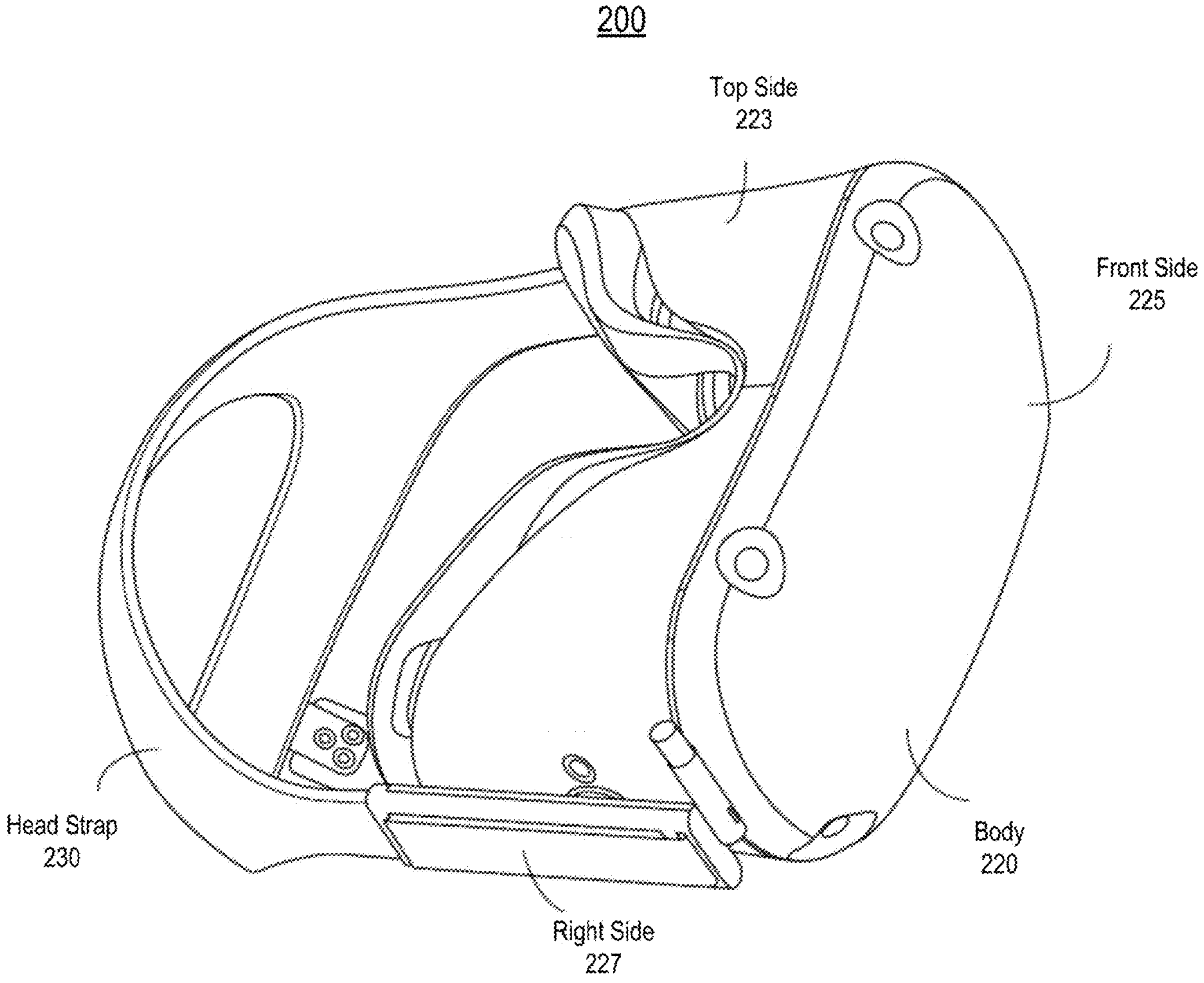

200
Top Side
223
Front Side
225
Body
220
Right Side
227
Head Strap
230

FIG. 2

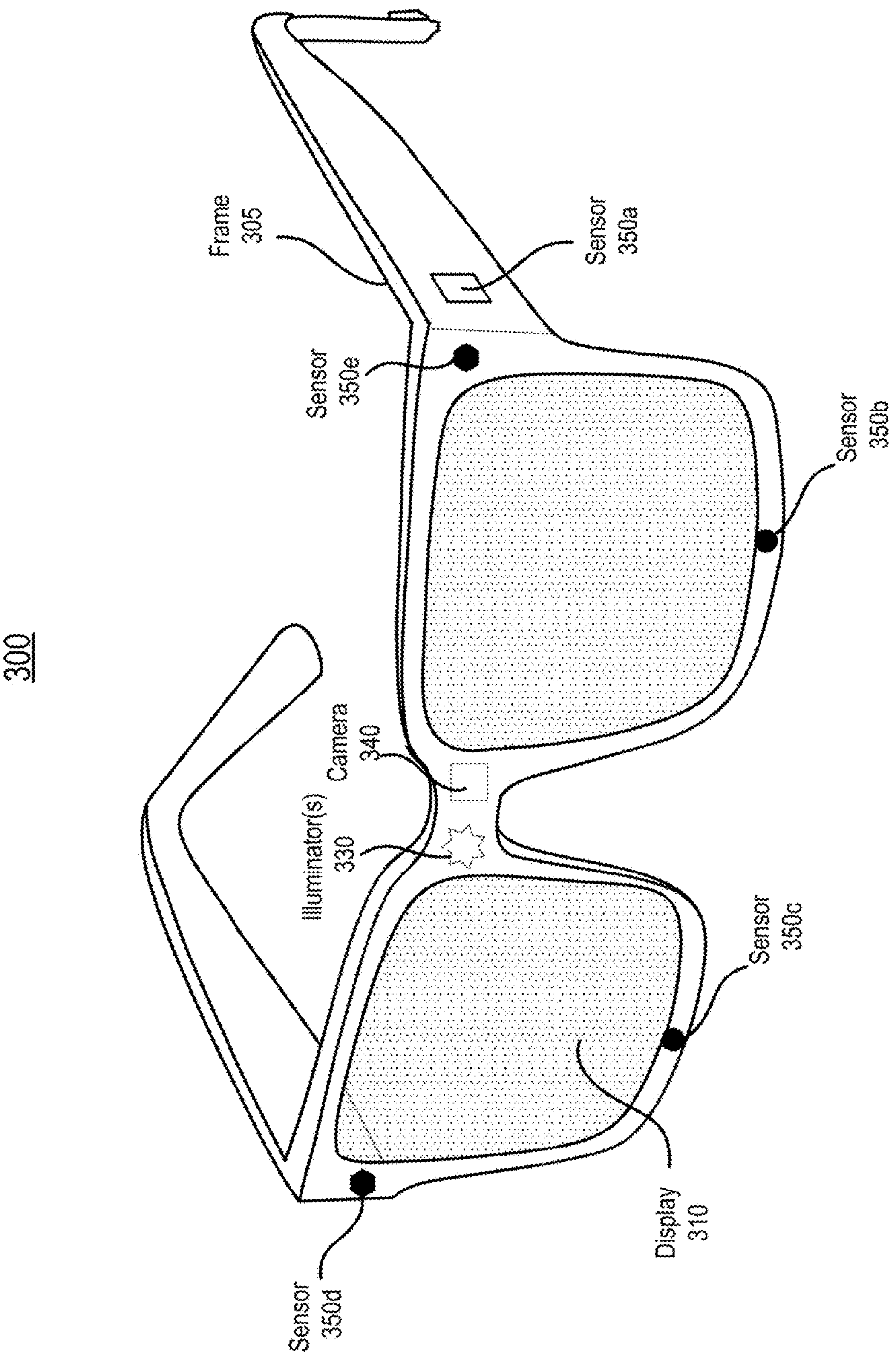

300
Frame 305
Sensor 350a
Sensor 350e
Sensor 350b
Camera 340
Illuminator(s) 330
Sensor 350c
Display 310
Sensor 350d

FIG. 3

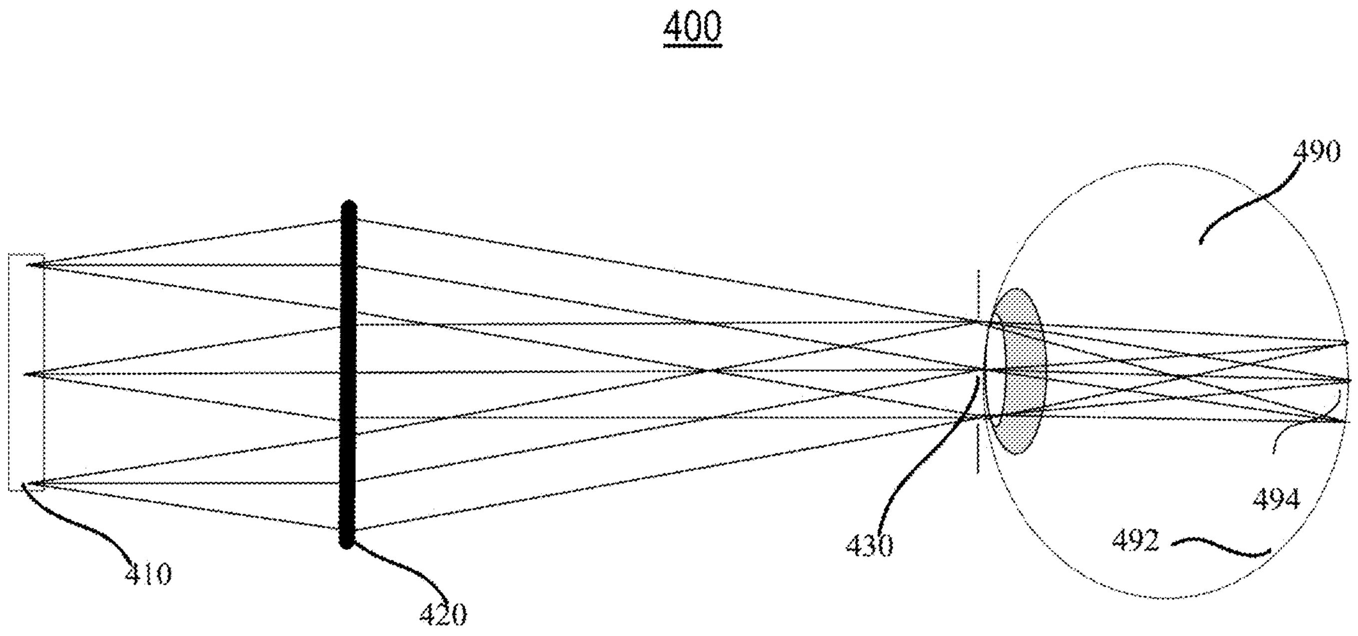


FIG. 4

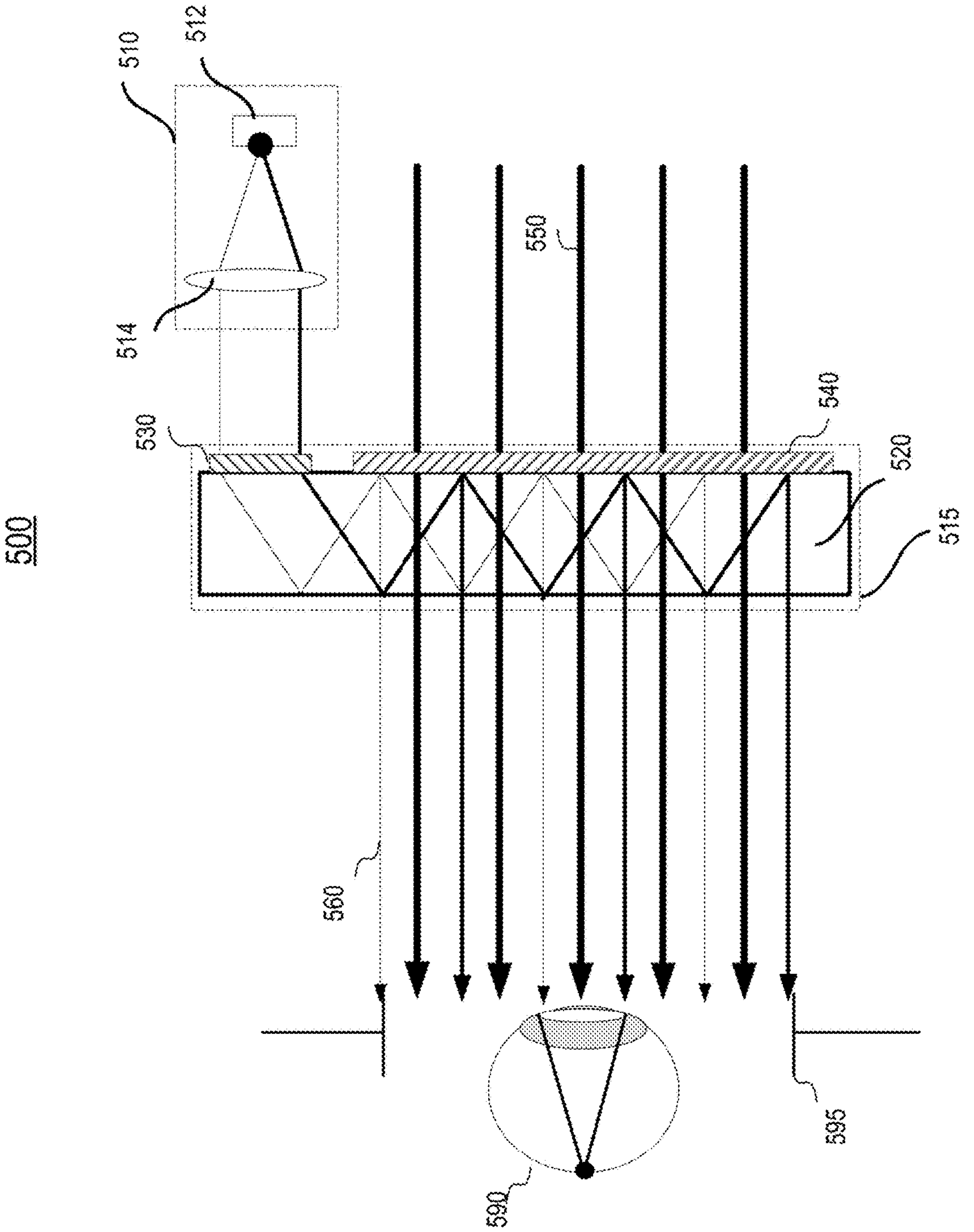


FIG. 5

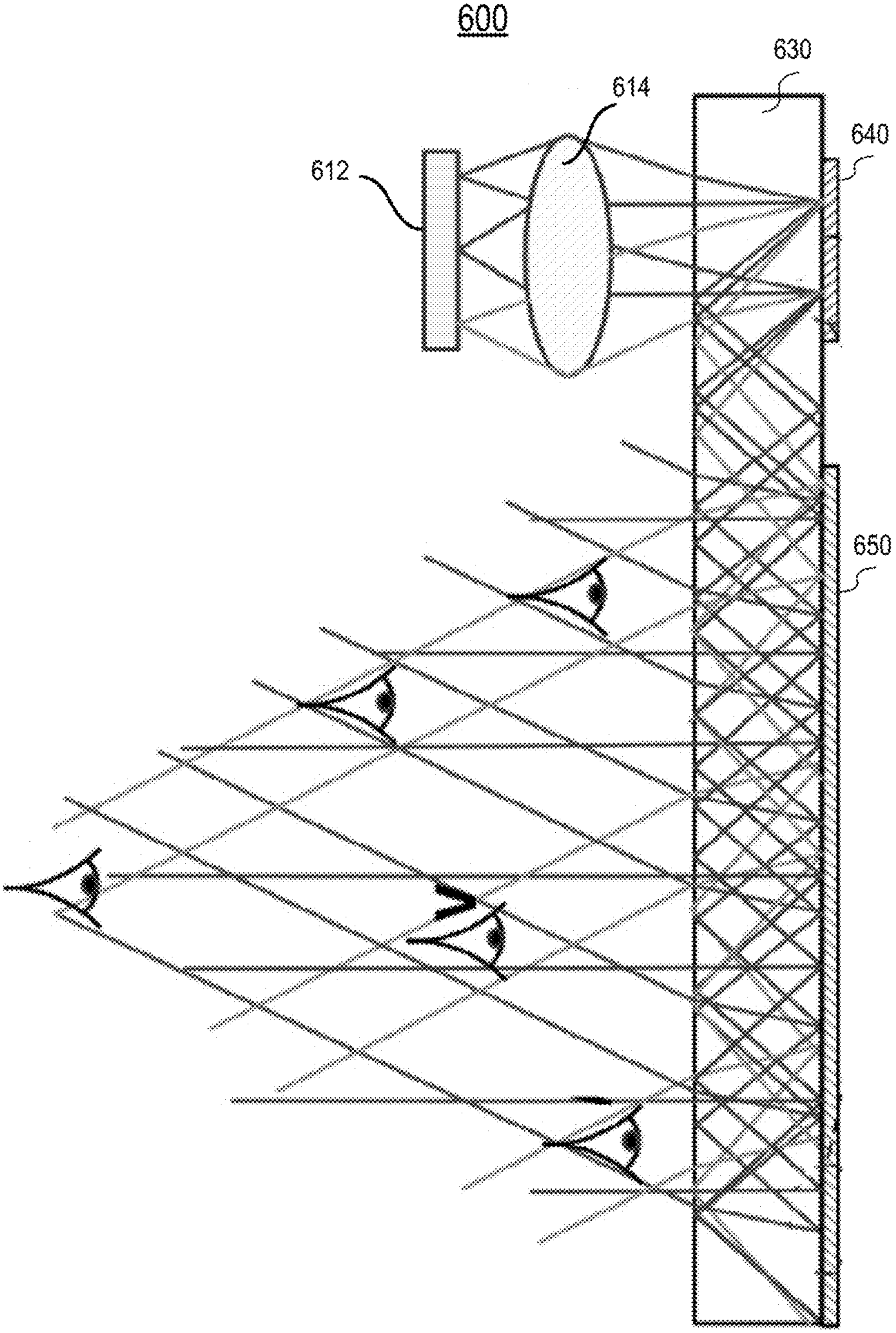


FIG. 6

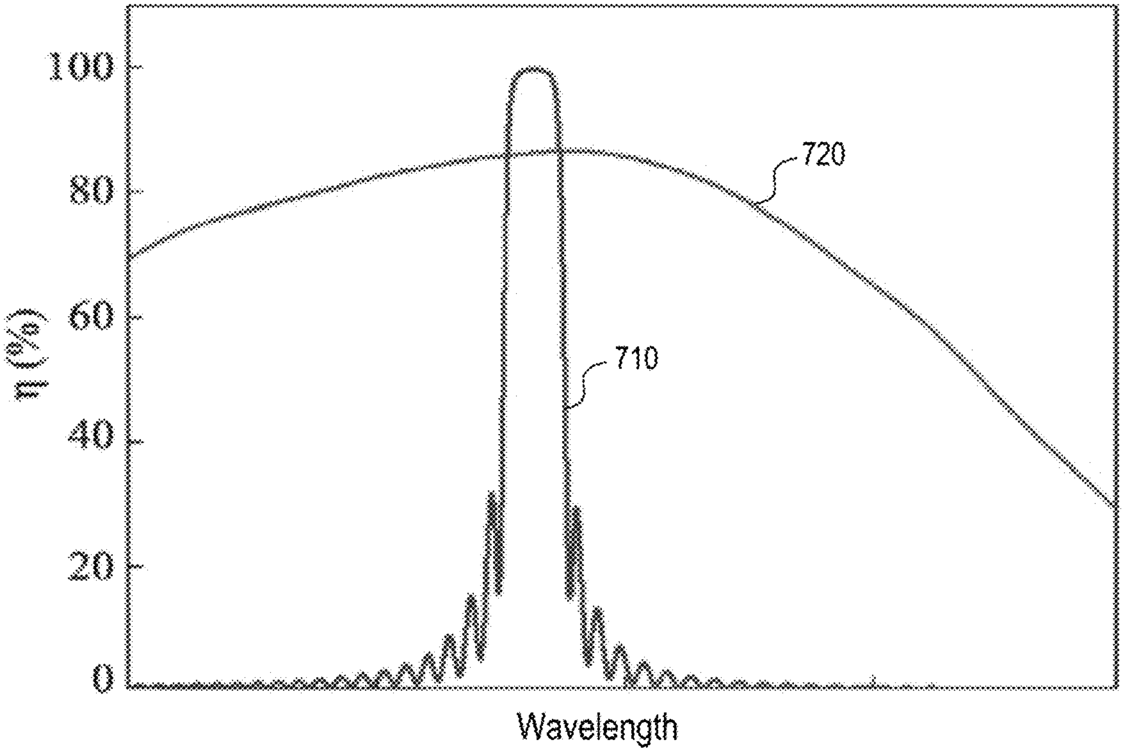

100
80
60
40
20
0
η (%)
720
710
Wavelength

FIG. 7A

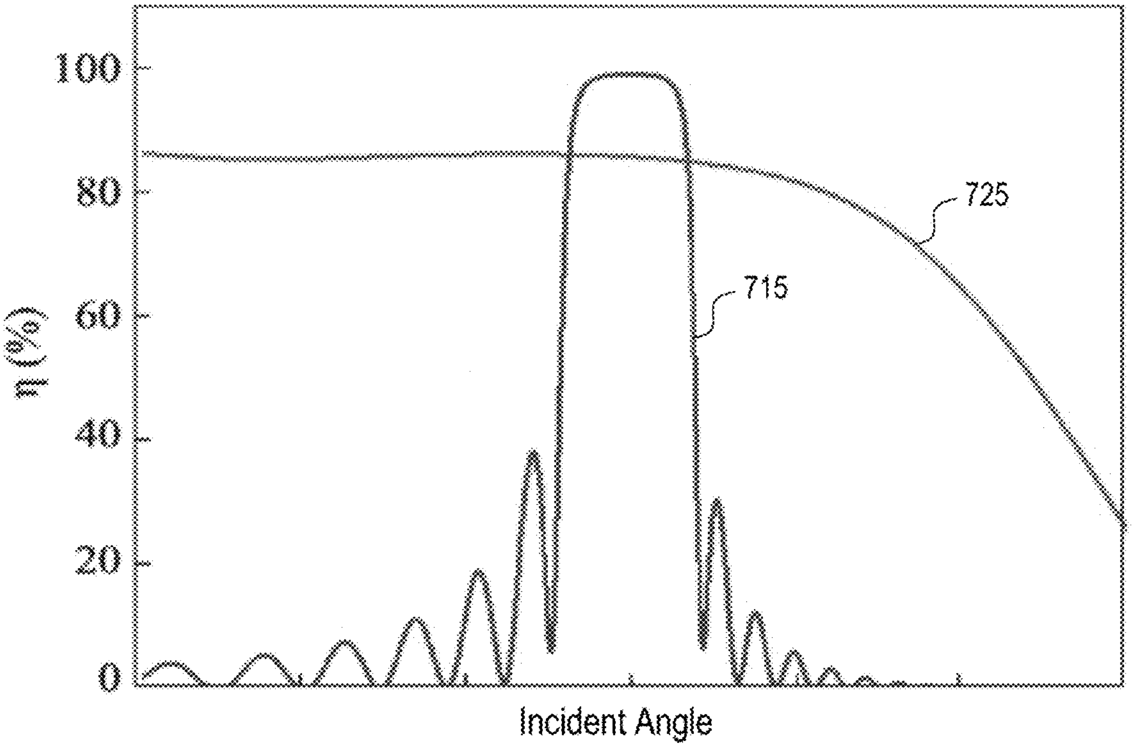

100
80
60
40
20
0
η (%)
725
715
Incident Angle

FIG. 7B

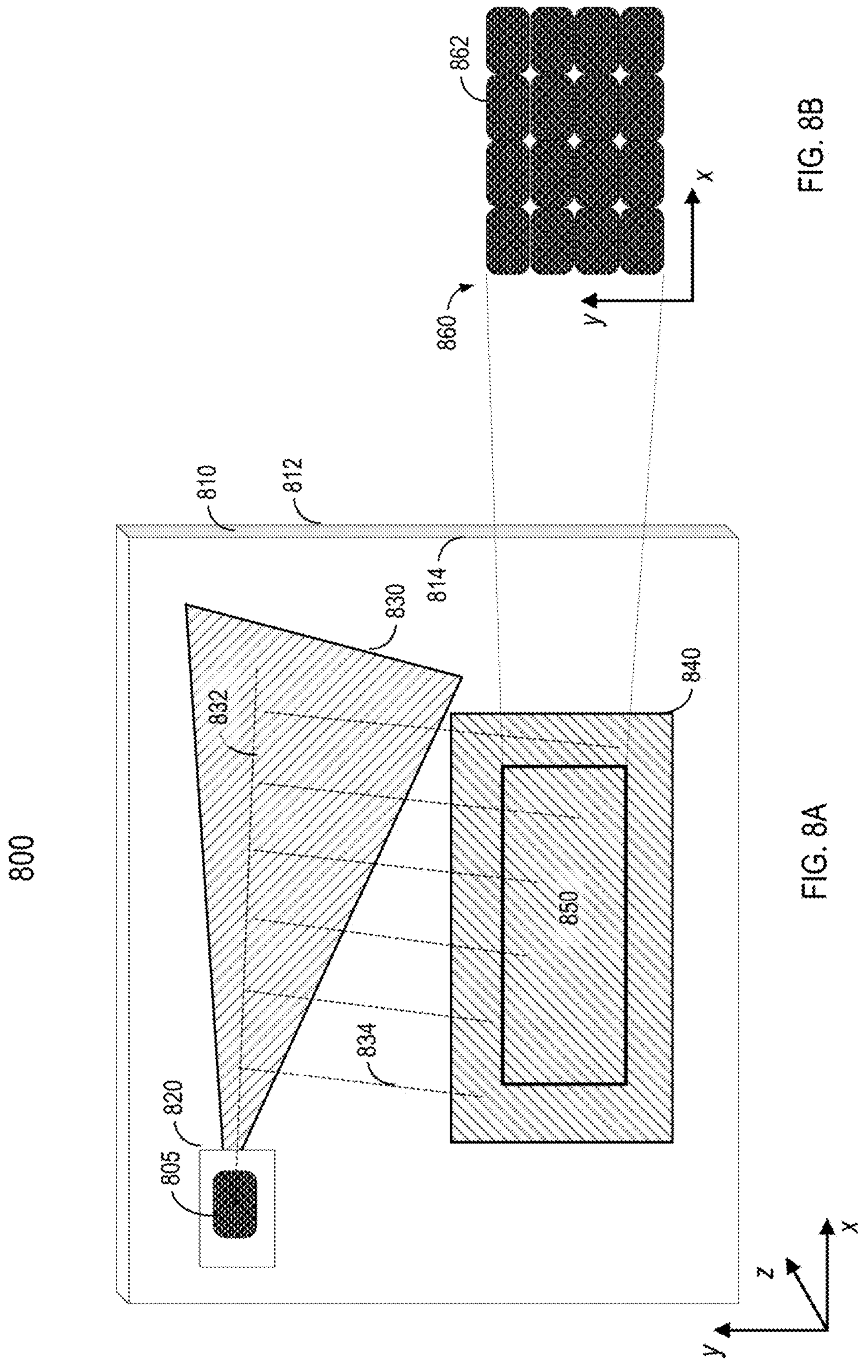


FIG. 8A

FIG. 8B

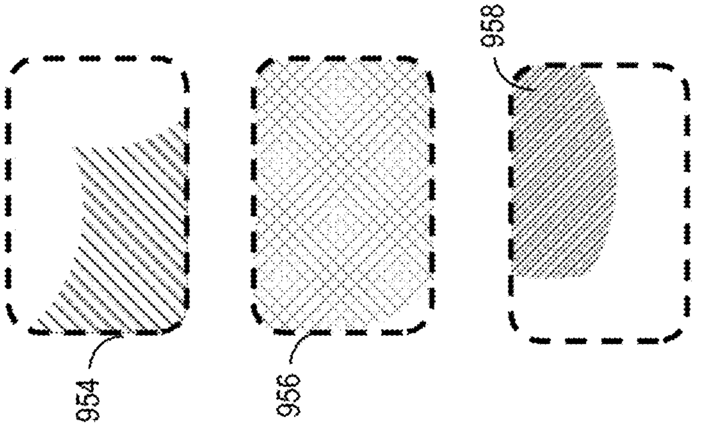

954
956
958

FIG. 9B

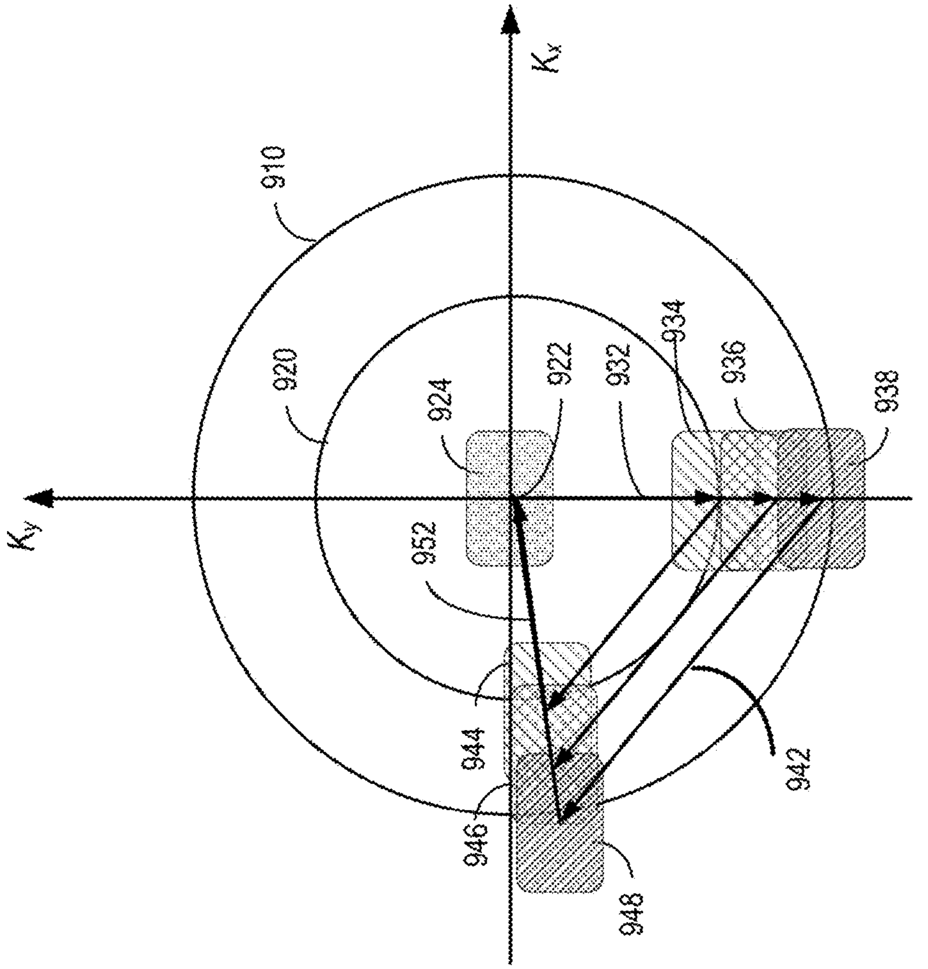

Ky
Kx
910
920
924
922
932
934
936
938
952
944
946
948
942

FIG. 9A

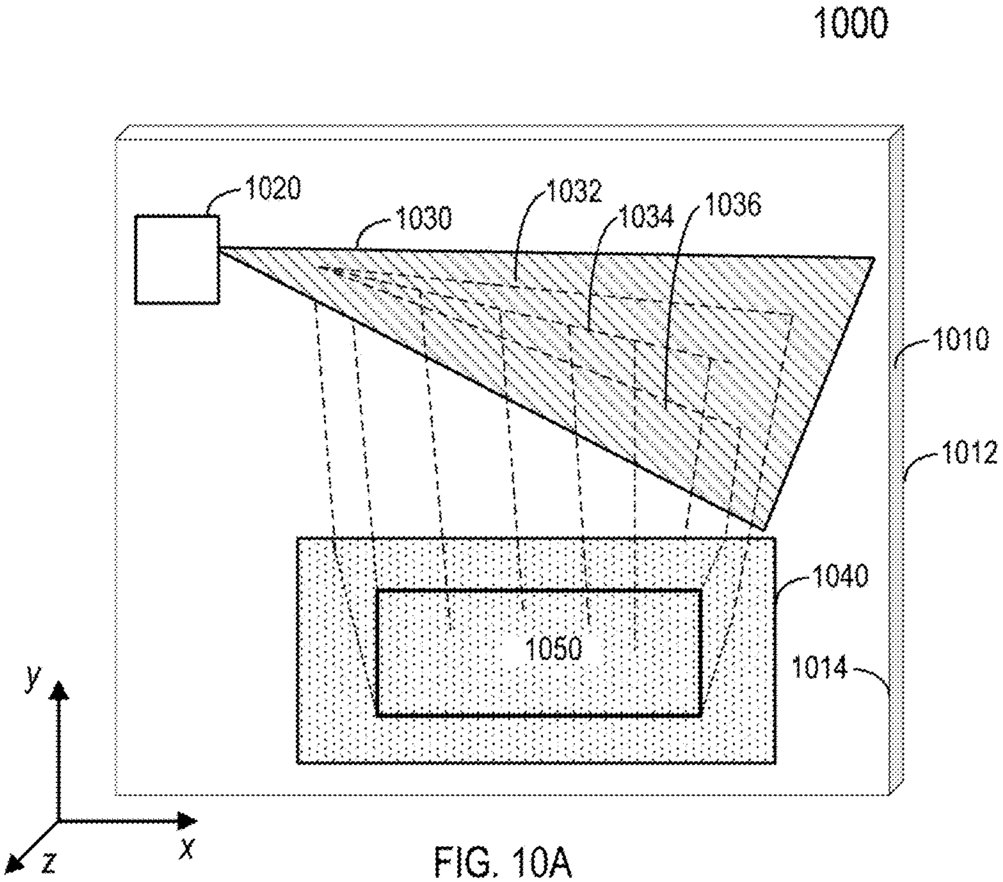


FIG. 10A

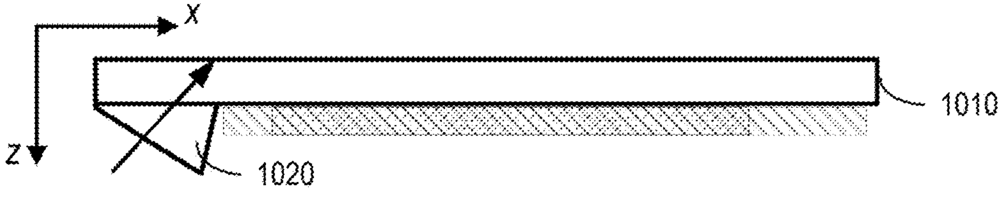


FIG. 10B

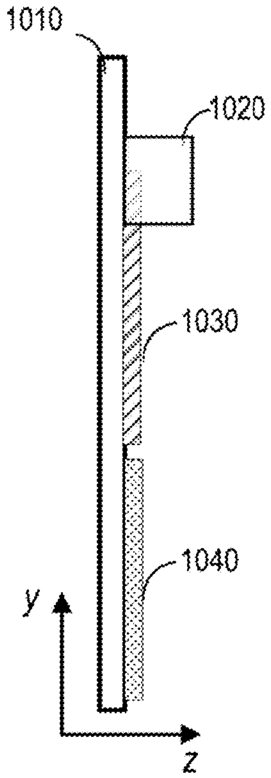


FIG. 10C

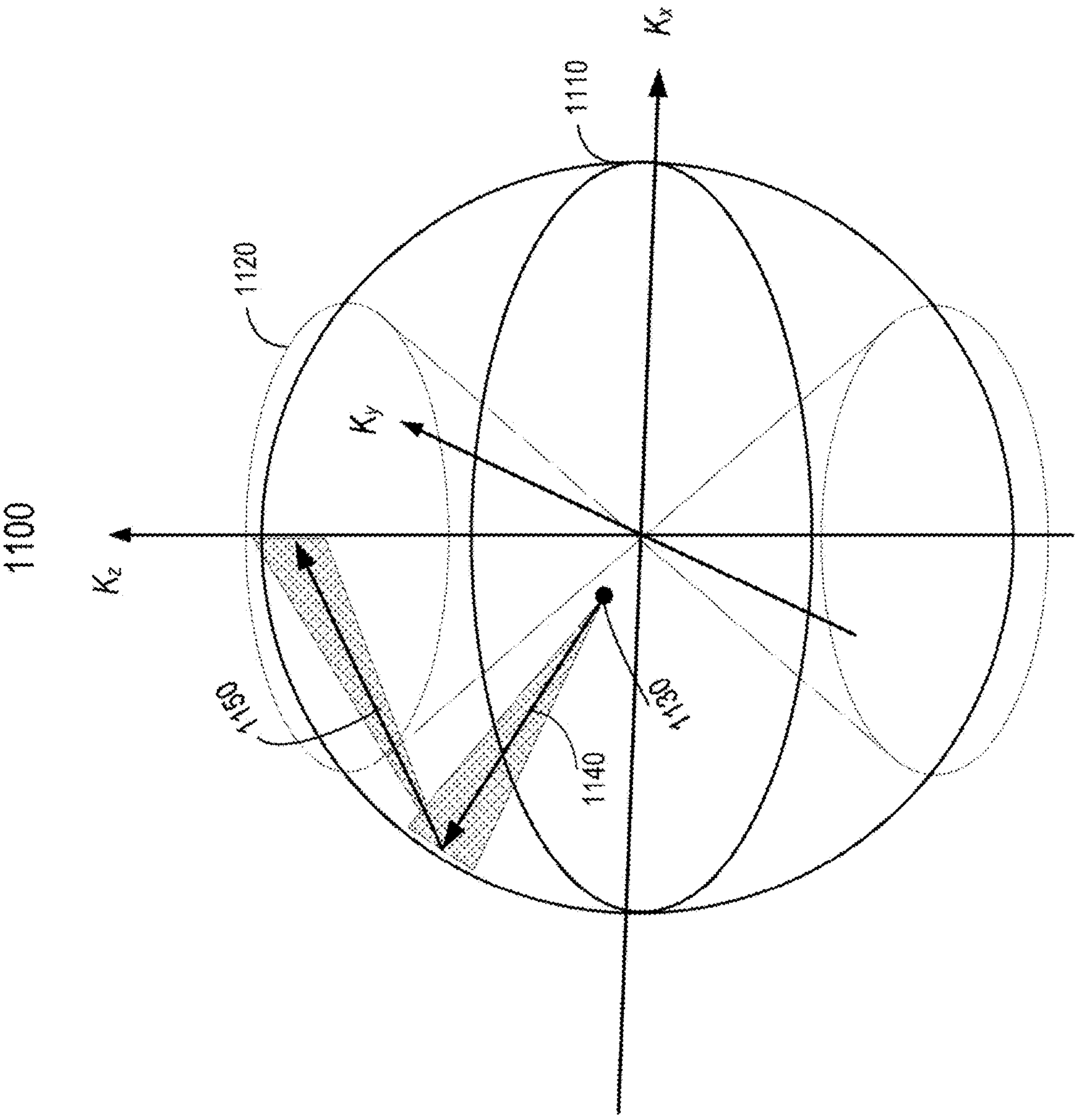


FIG. 11

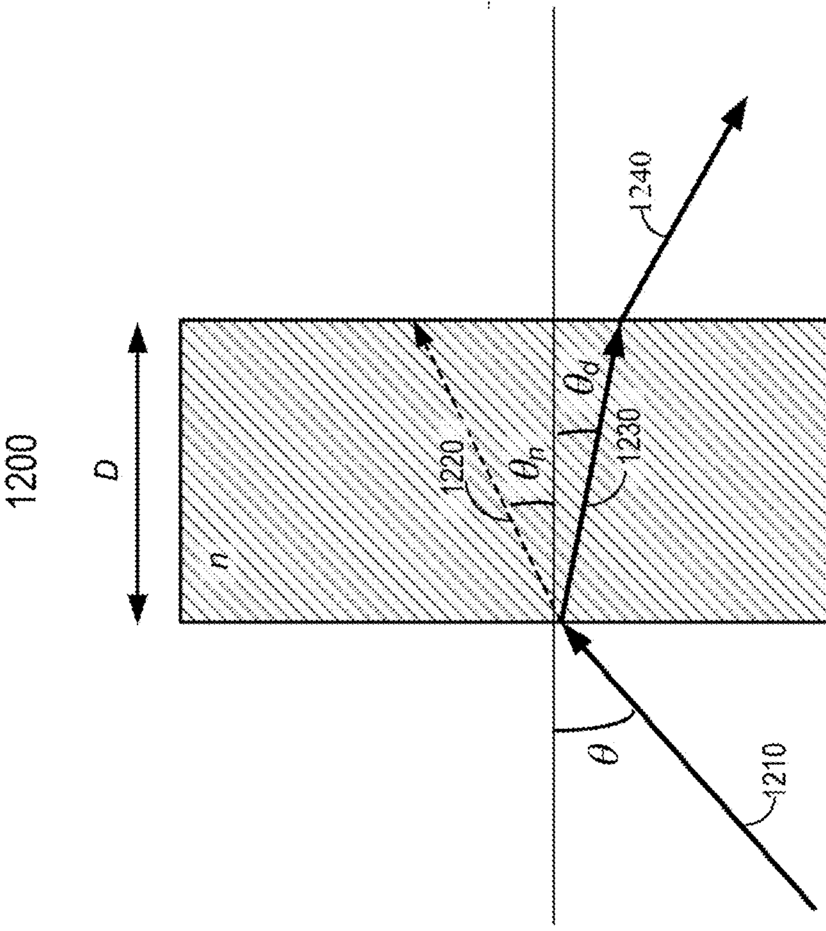


FIG. 12A

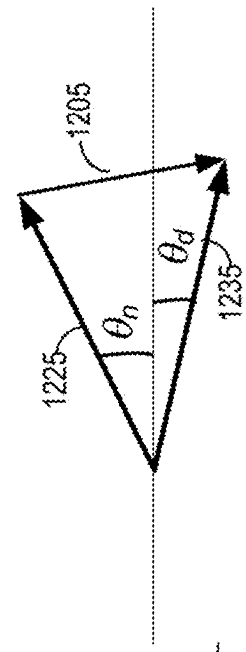


FIG. 12B

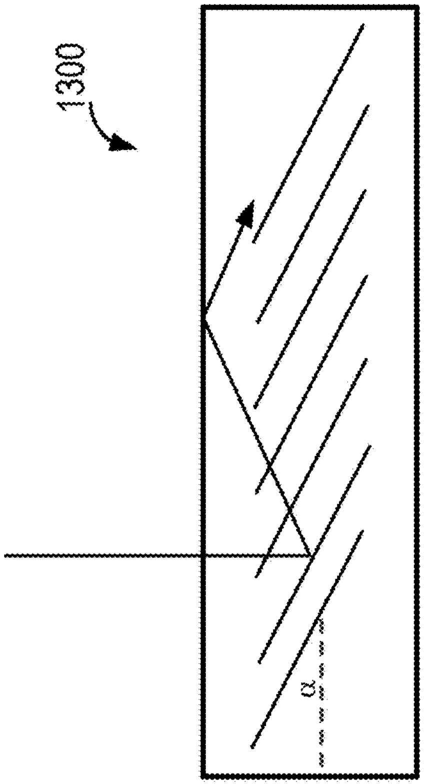


FIG. 13A

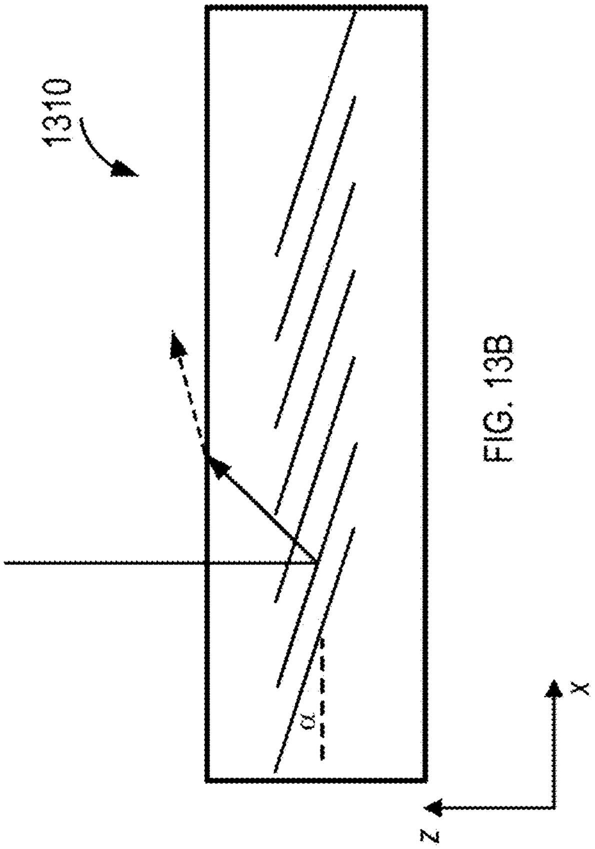


FIG. 13B

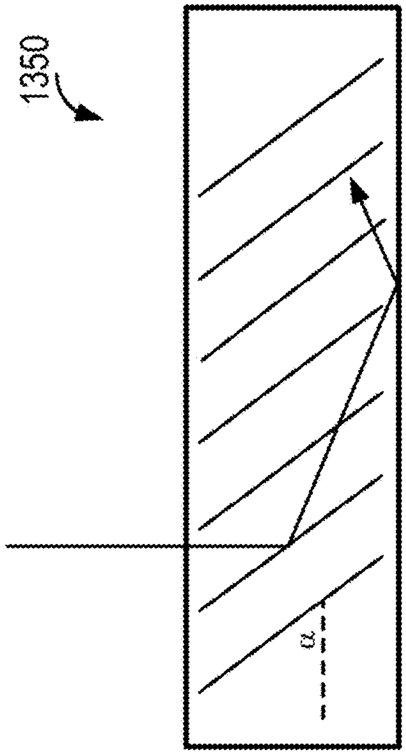


FIG. 13C

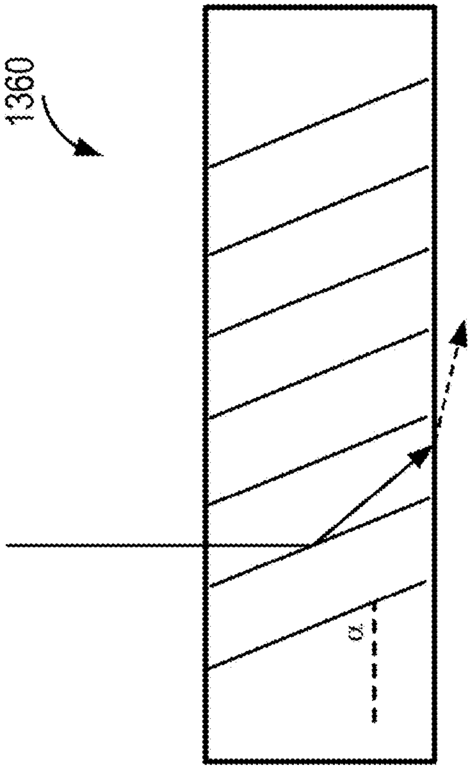


FIG. 13D

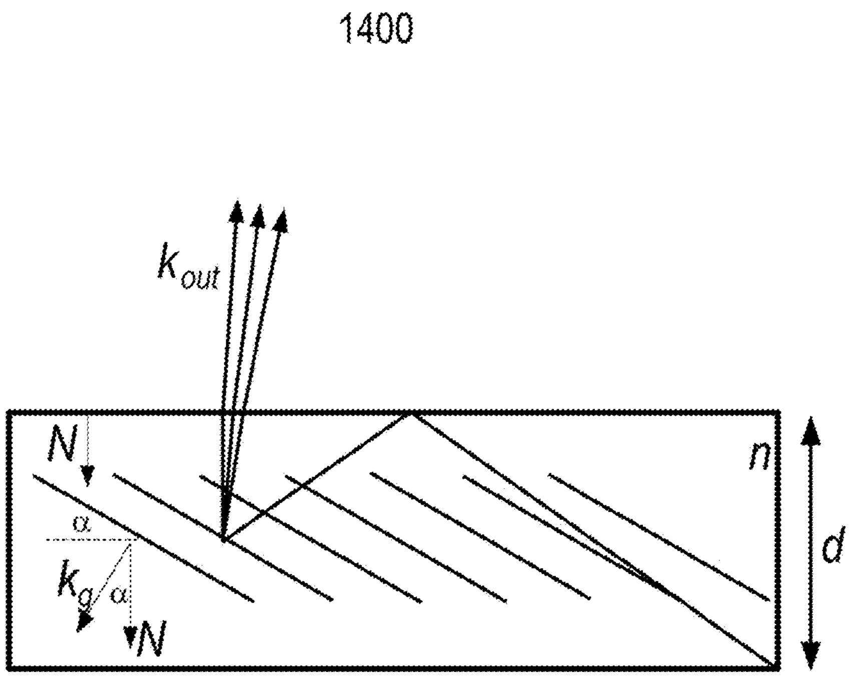
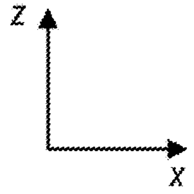


FIG. 14A



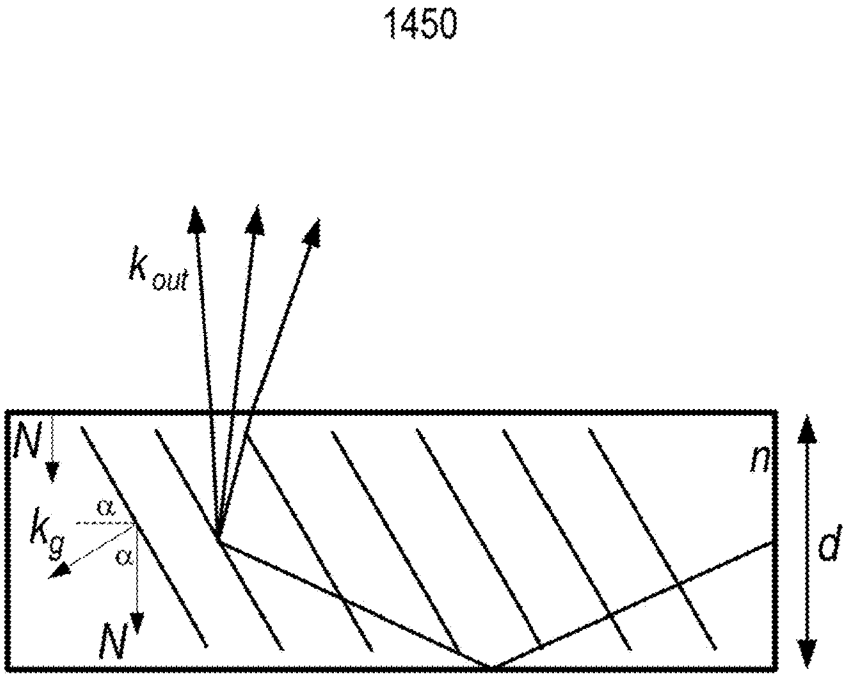


FIG. 14B

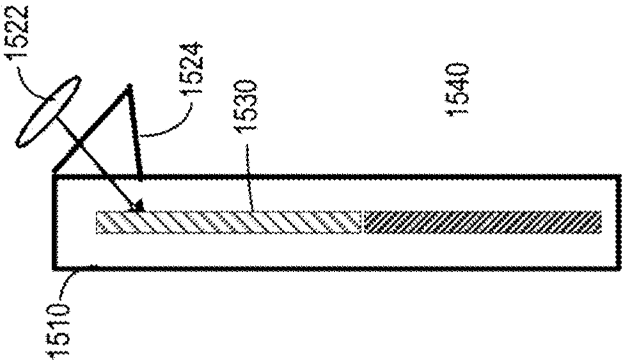


FIG. 15B

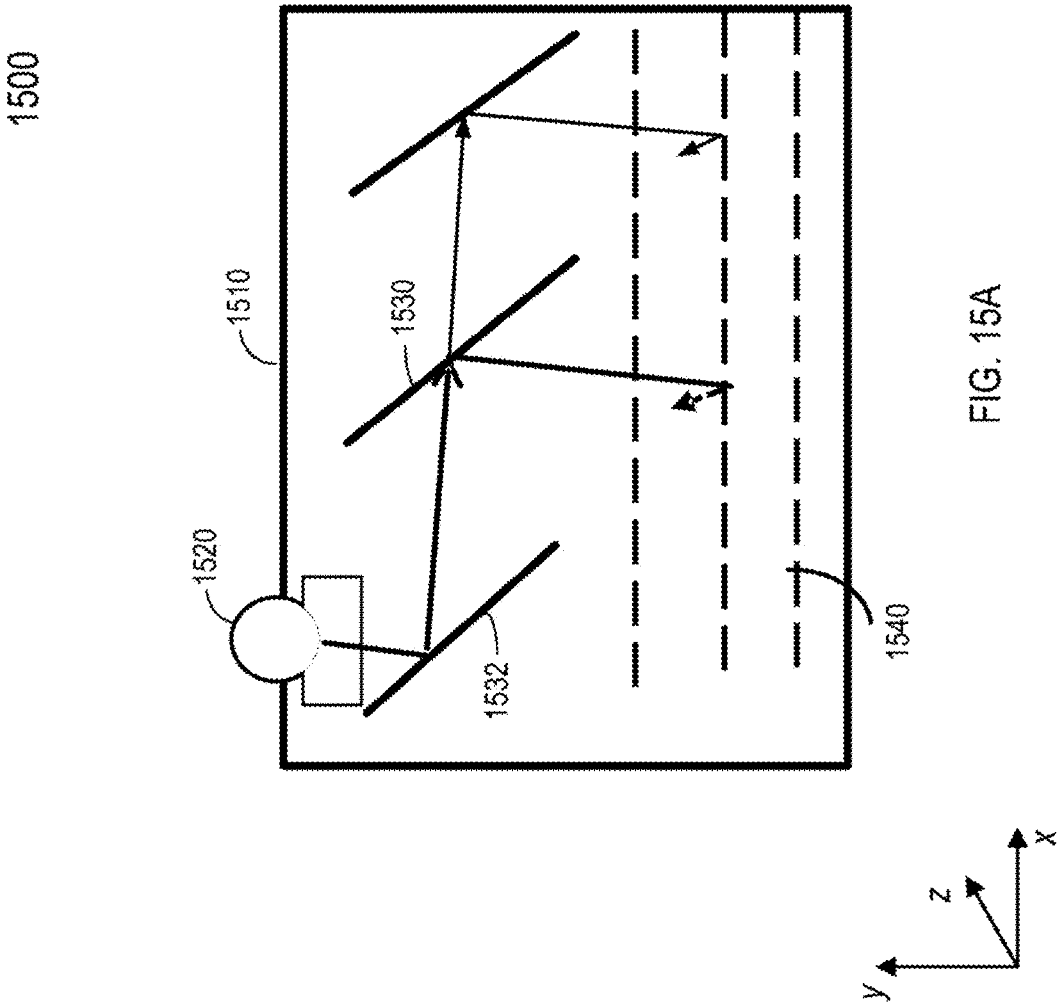


FIG. 15A

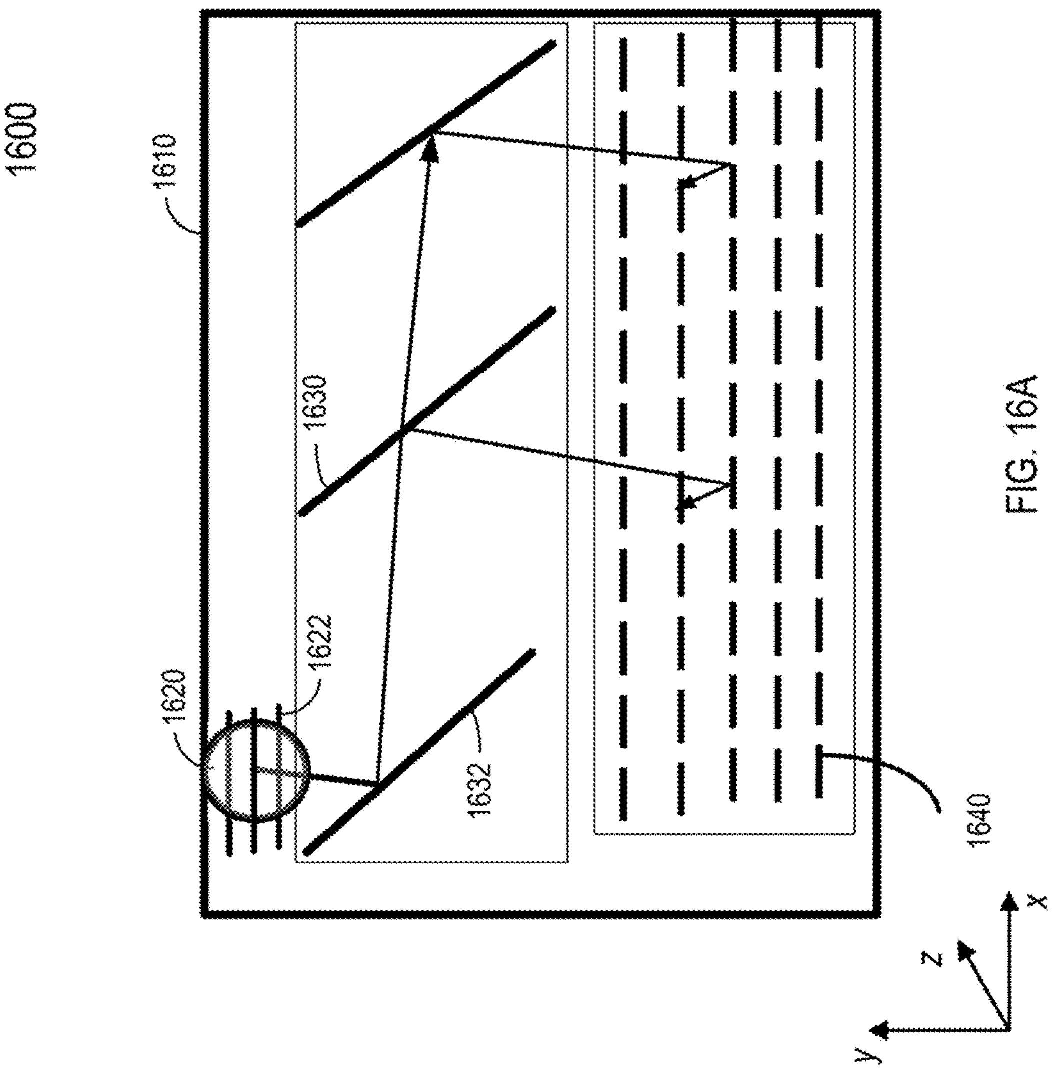


FIG. 16A

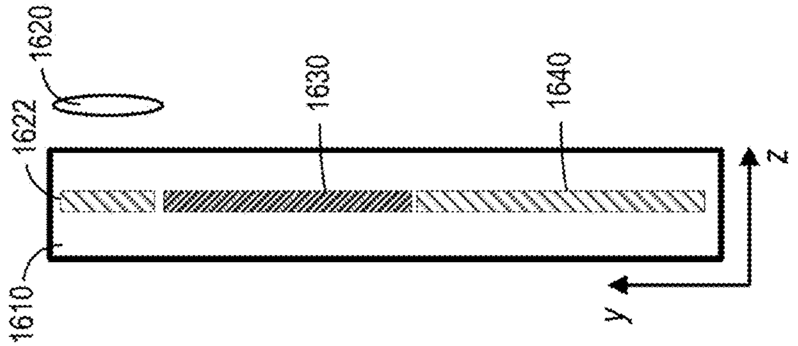


FIG. 16B

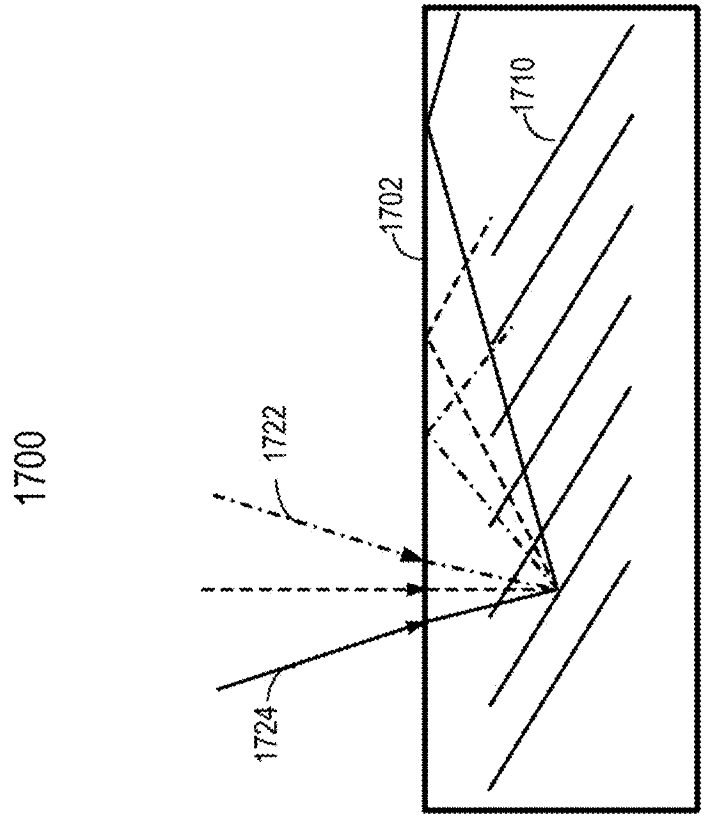


FIG. 17A

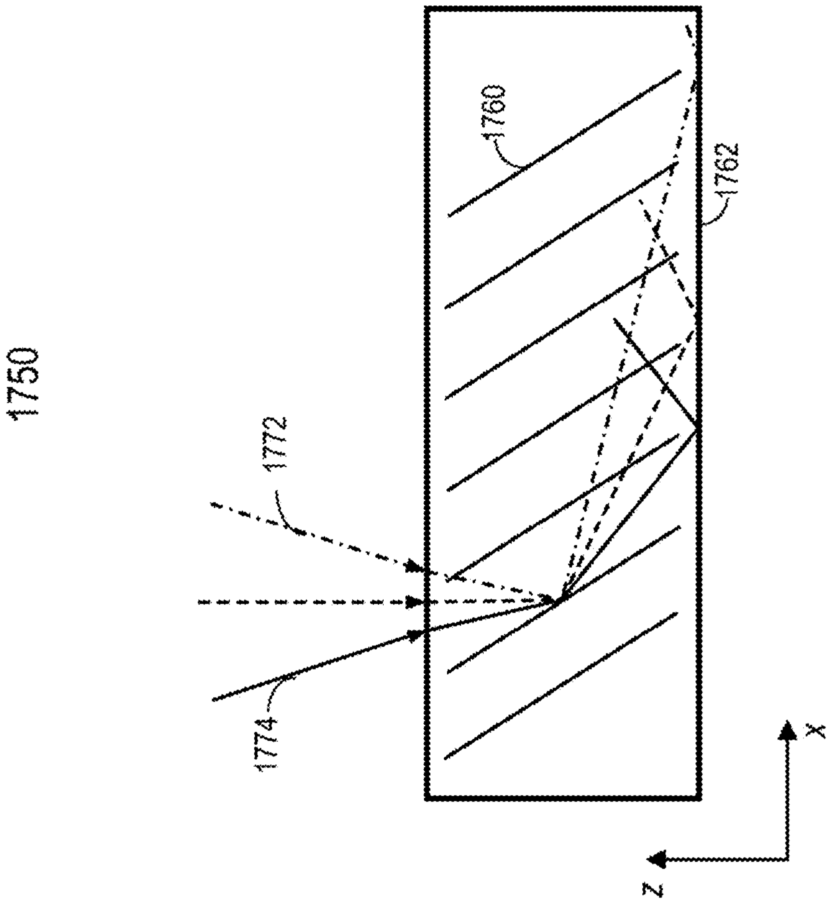


FIG. 17B

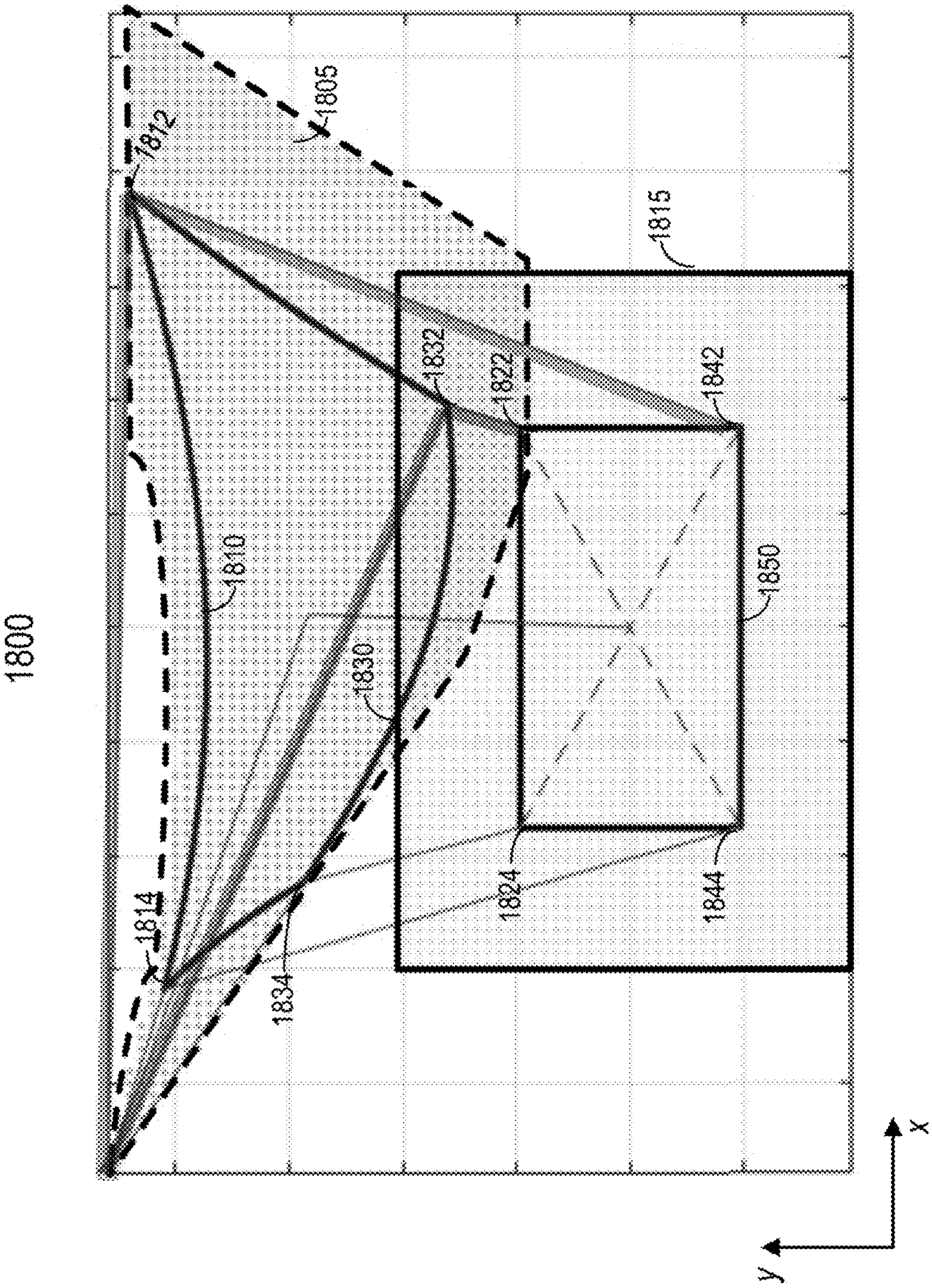

1800
1805
1812
1815
1842
1822
1832
1810
1850
1830
1814
1834
1824
1844
x
y

FIG. 18

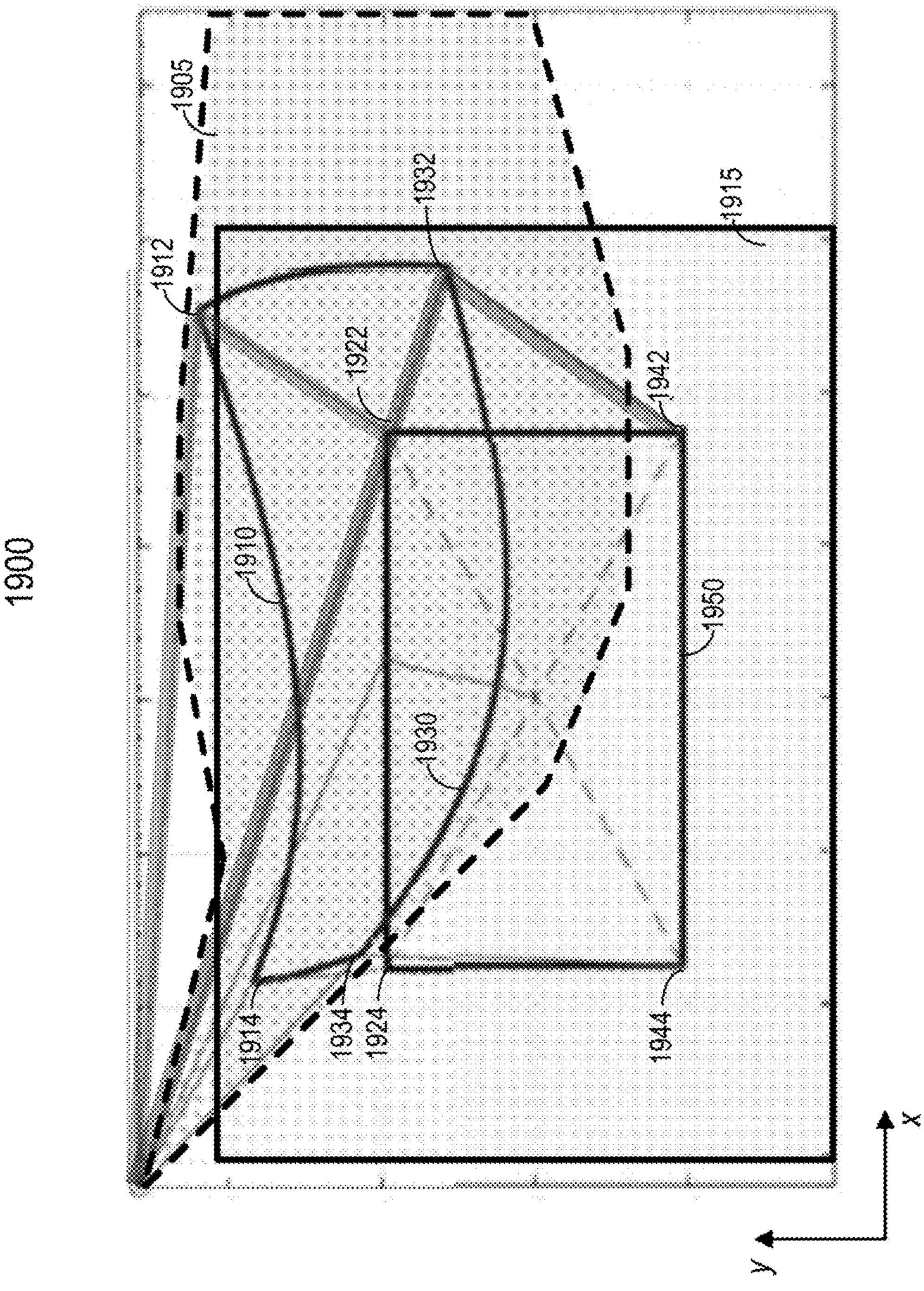

1900
1905
1912
1932
1915
1922
1942
1910
1950
1930
1914
1934
1924
1944
x
y

FIG. 19

2000

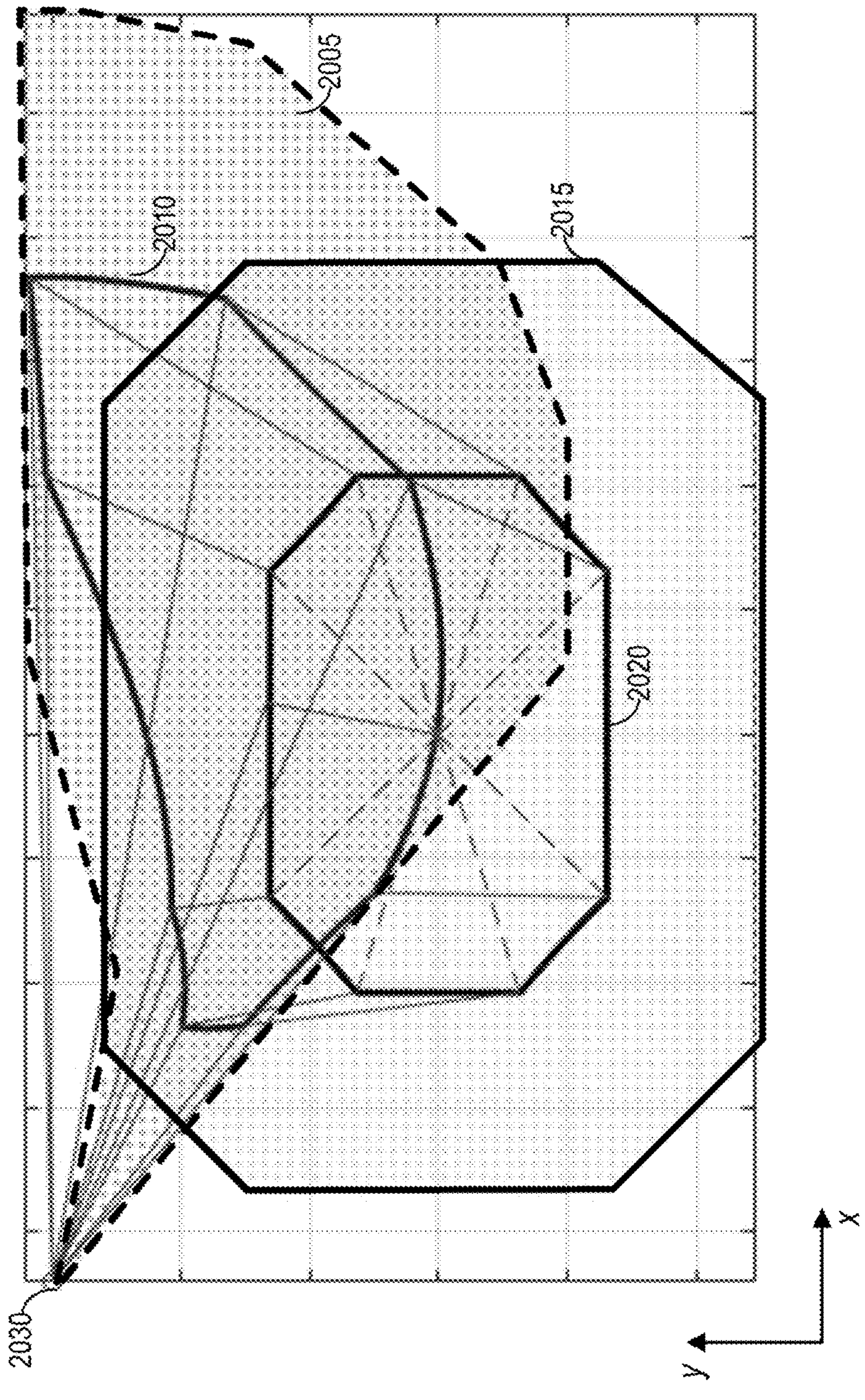


FIG. 20

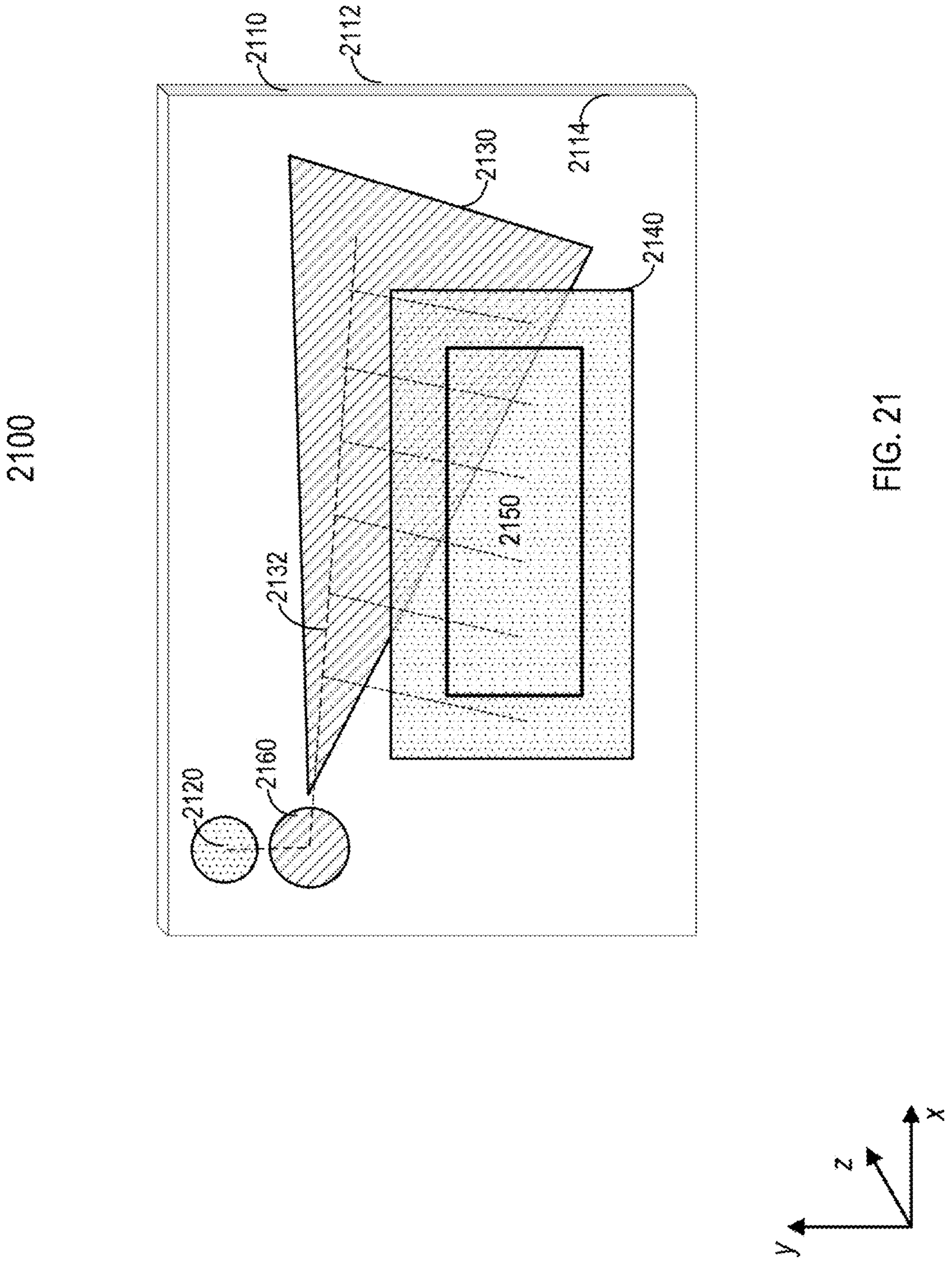


FIG. 21

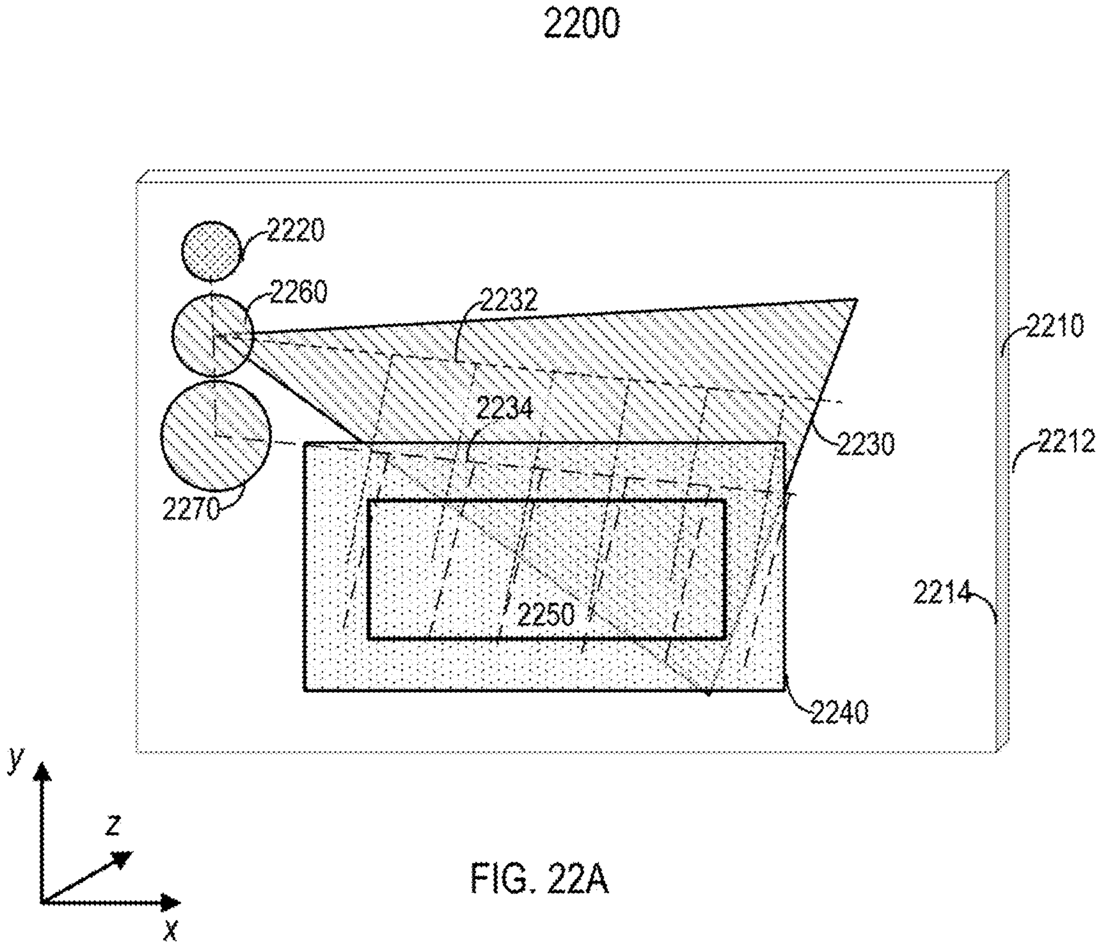


FIG. 22A

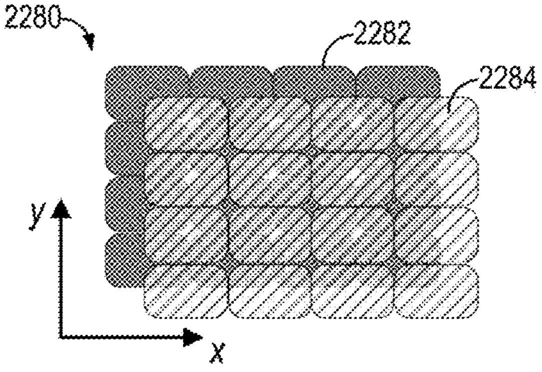


FIG. 22B

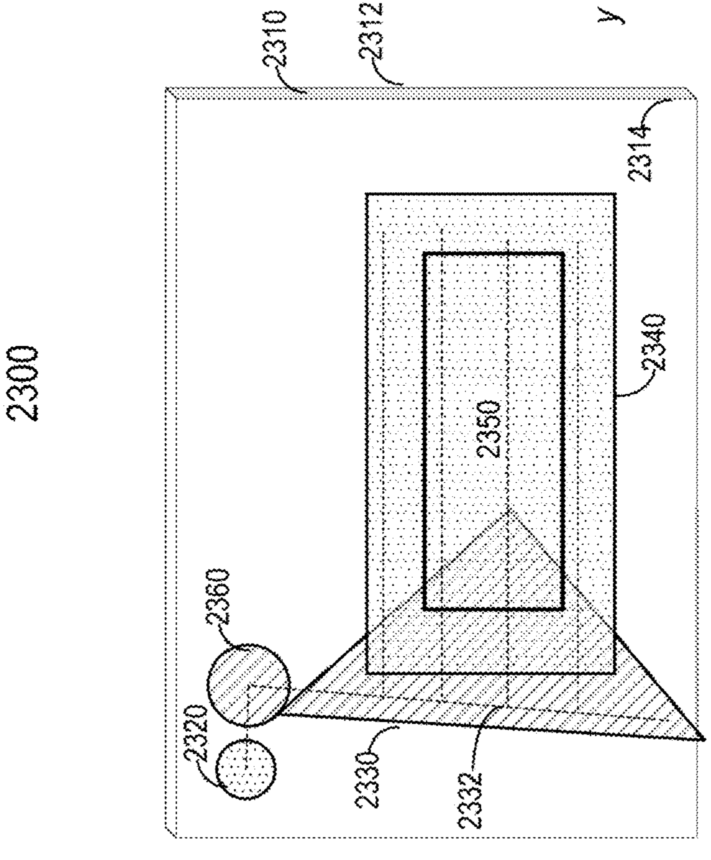
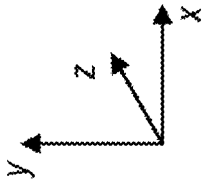


FIG. 23A



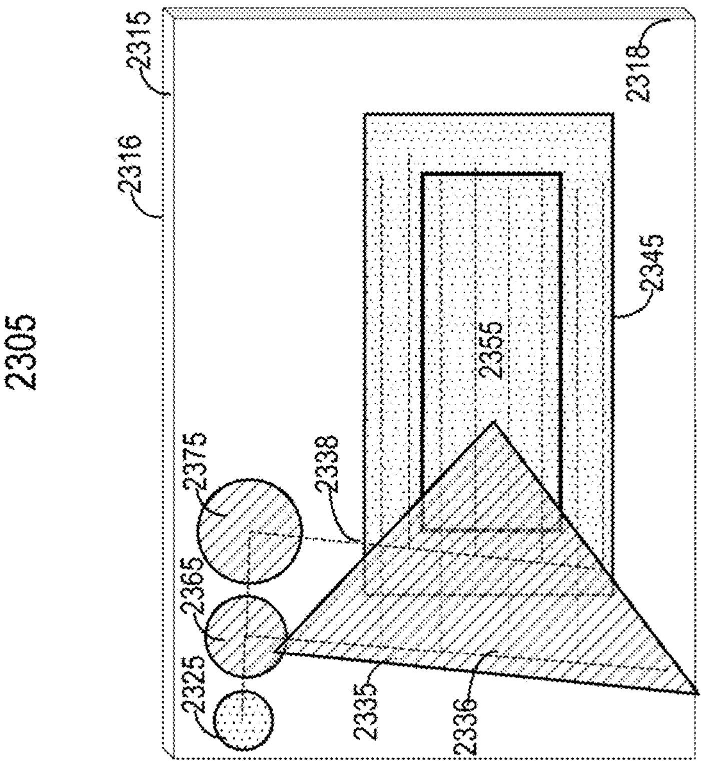


FIG. 23B

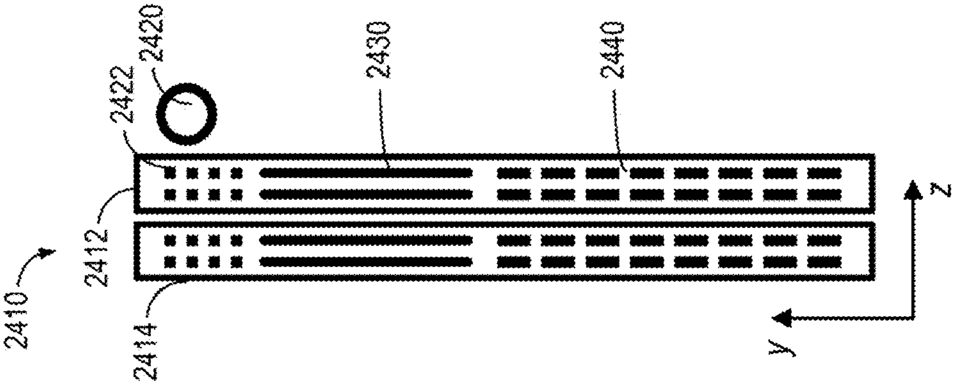


FIG. 24B

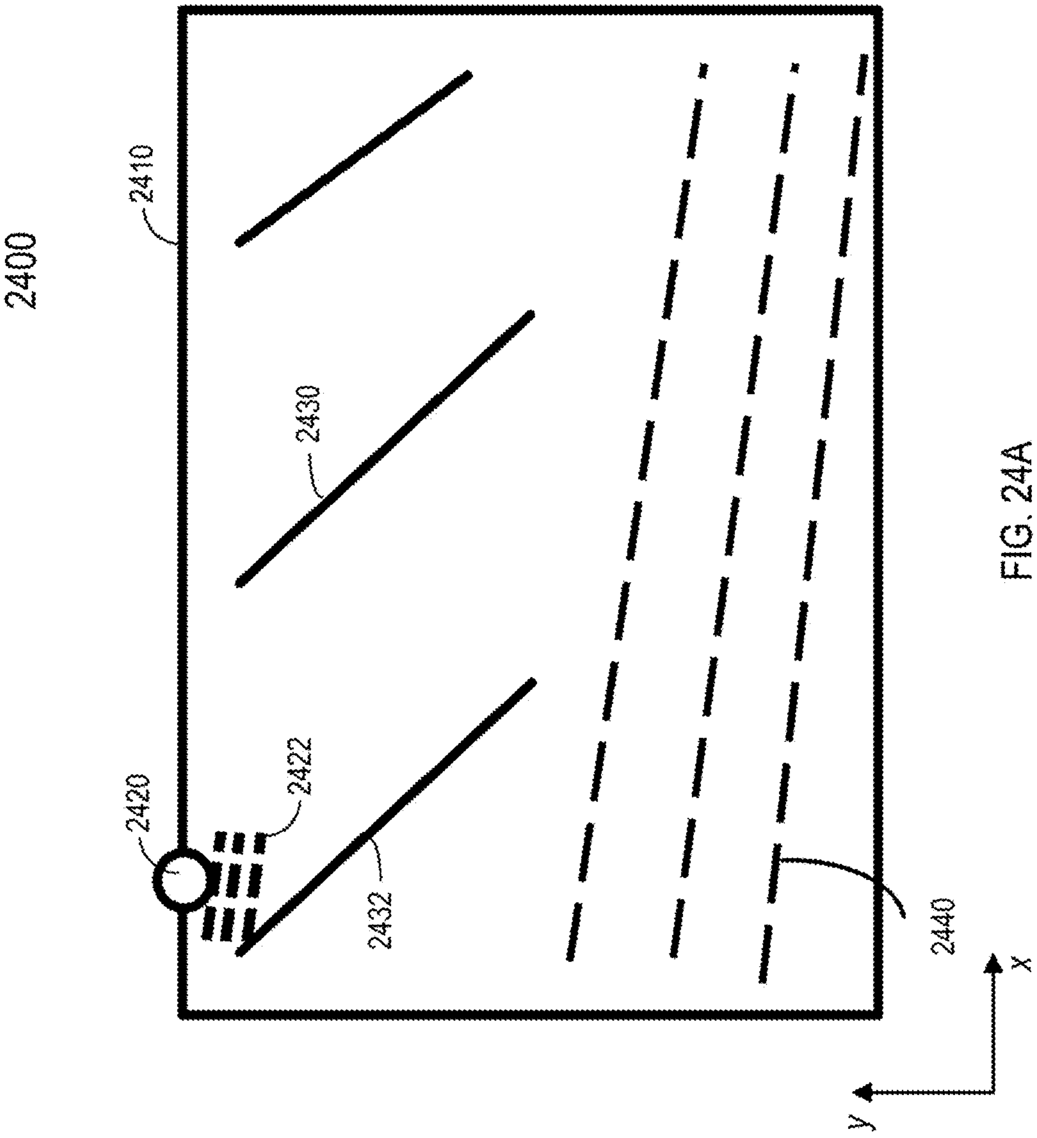


FIG. 24A

2500

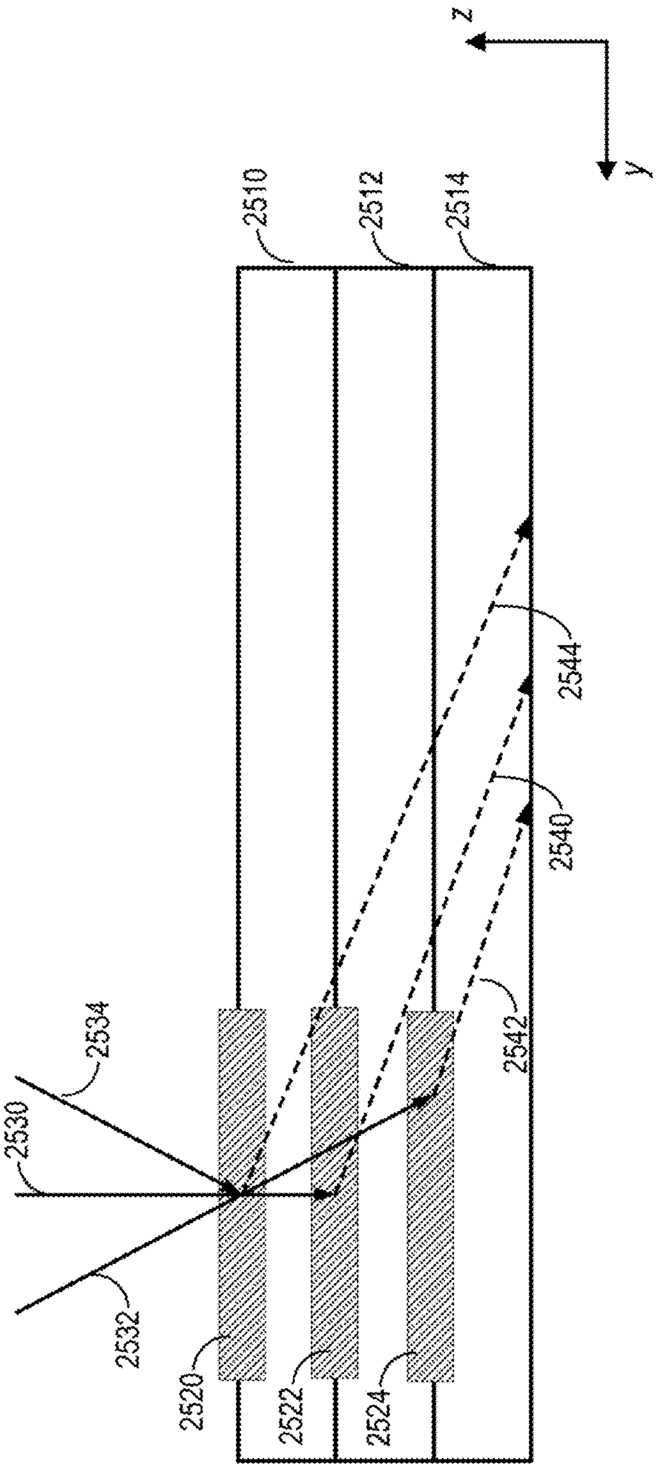

z
y
2510
2512
2514
2544
2540
2542
2534
2530
2532
2520
2522
2524

FIG. 25

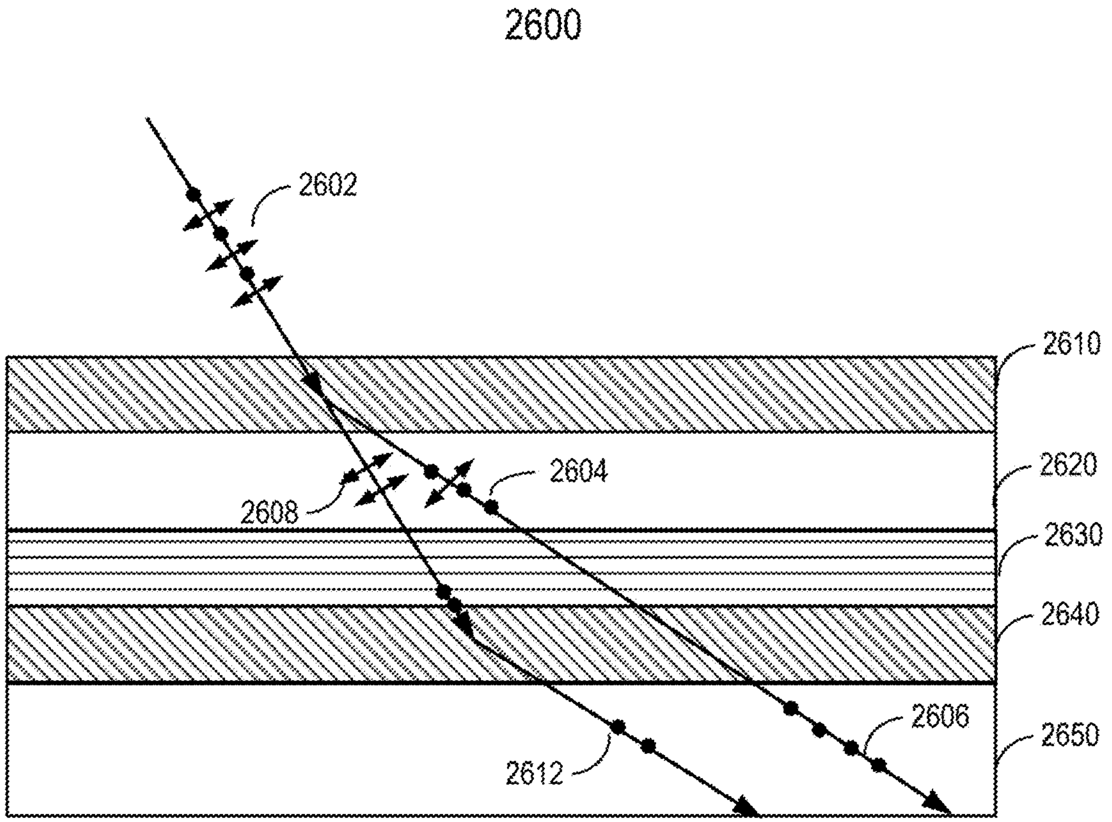


FIG. 26

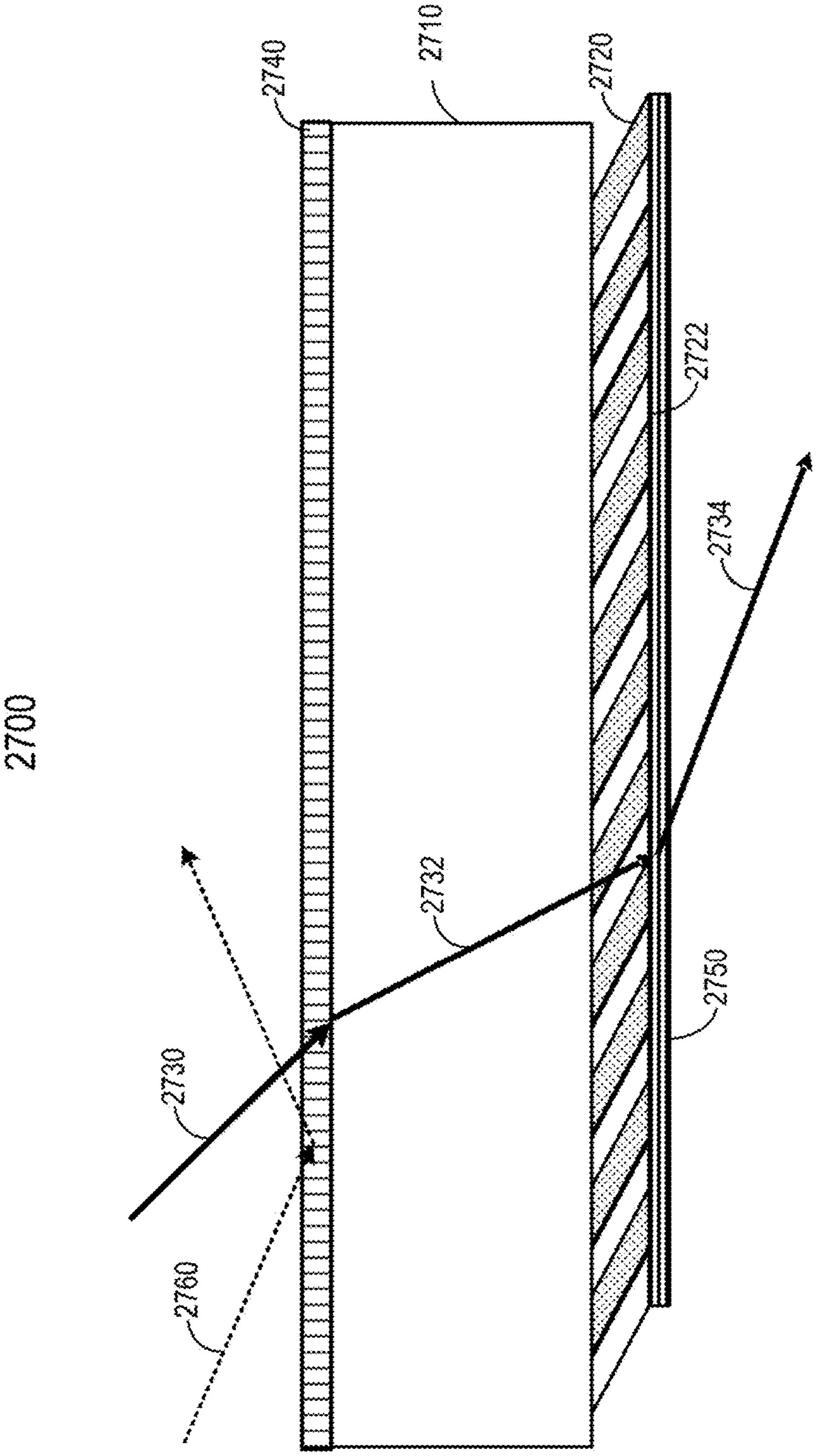


FIG. 27

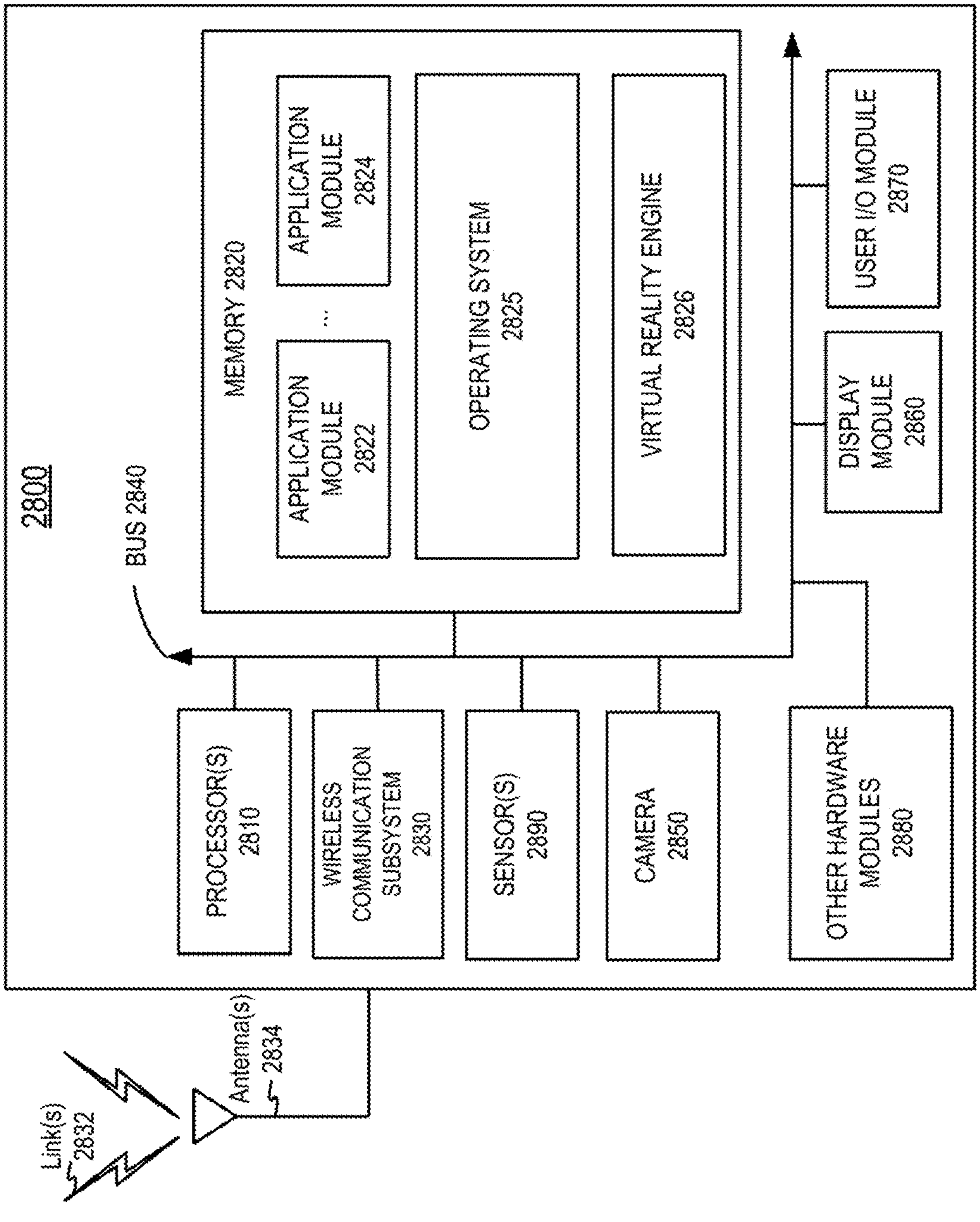

2800
BUS 2840
MEMORY 2820
APPLICATION MODULE 2822
...
APPLICATION MODULE 2824
OPERATING SYSTEM 2825
VIRTUAL REALITY ENGINE 2826
PROCESSOR(S) 2810
WIRELESS COMMUNICATION SUBSYSTEM 2830
SENSOR(S) 2890
CAMERA 2850
OTHER HARDWARE MODULES 2880
DISPLAY MODULE 2860
USER I/O MODULE 2870
Antenna(s) 2834
Link(s) 2832

FIG. 28

DISPERSION COMPENSATION IN VOLUME BRAGG GRATING-BASED WAVEGUIDE DISPLAY

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This patent application claims priority to U.S. Provisional Patent Application Ser. No. 62/891,167, filed Aug. 23, 2019, entitled "Volume Bragg Grating-Based Waveguide Display," the disclosure of which is hereby incorporated by reference in its entirety for all purposes.

BACKGROUND

[0002] An artificial reality system, such as a head-mounted display (HMD) or heads-up display (HUD) system, generally includes a near-eye display (e.g., in the form of a headset or a pair of glasses) configured to present content to a user via an electronic or optic display within, for example, about 10-20 mm in front of the user's eyes. The near-eye display may display virtual objects or combine images of real objects with virtual objects, as in virtual reality (VR), augmented reality (AR), or mixed reality (MR) applications. For example, in an AR system, a user may view both images of virtual objects (e.g., computer-generated images (CGIs)) and the surrounding environment by, for example, seeing through transparent display glasses or lenses (often referred to as optical see-through).

[0003] One example of an optical see-through AR system may use a waveguide-based optical display, where light of projected images may be coupled into a waveguide (e.g., a transparent substrate), propagate within the waveguide, and be coupled out of the waveguide at different locations. In some implementations, the light of the projected images may be coupled into or out of the waveguide using a diffractive optical element, such as a grating. Light from the surrounding environment may pass through a see-through region of the waveguide and reach the user's eyes as well.

SUMMARY

[0004] This disclosure relates generally to volume Bragg grating-based waveguide displays for near-eye display. More specifically, disclosed herein are techniques for expanding the eyebox, reducing display haze, reducing physical size, improving optical efficiency, reducing optical artifacts, and increasing field of view of optical see-through near-eye display systems using volume Bragg grating (VBG) couplers. Various inventive embodiments are described herein, including devices, systems, methods, and the like.

[0005] According to some embodiments, a waveguide display may include a substrate transparent to visible light, and a first VBG, a second VBG, and a third VBG coupled to the substrate. The first VBG may be configured to couple display light into the substrate as guided wave towards a first region of the second VBG. The second VBG may be configured to diffract, at the first region of the second VBG, the display light from the first VBG to a first direction (e.g., x direction), and diffract, at two or more regions of the second VBG along the first direction, the display light from the first region to a second direction (e.g., y direction) towards the third VBG. The third VBG may be configured to couple the display light from each of the two or more regions of the second VBG out of the substrate at two or more regions of the third VBG along the second direction. The first VBG and the third VBG may have a same grating vector in a plane (e.g., x-y plane) perpendicular to a surface normal direction of the substrate, and may have a same grating vector or opposite grating vectors in the surface normal (e.g., z) direction of the substrate. In some embodiments, the first region of the second VBG and the second region of the second VBG may have a same grating vector in a plane perpendicular to a surface normal direction of the substrate, and may have a same grating vector and/or opposite grating vectors in the surface normal direction of the substrate.

[0006] In some embodiments of the waveguide display, the first VBG, the second VBG, and the third VBG may be configured to diffract the display light from a same field of view range and in a same wavelength range. Each of the first VBG, the second VBG, and the third VBG includes a reflective VBG or a transmissive VBG. In some embodiments, the third VBG may include a transmissive VBG, and the second VBG may overlap with the third VBG in a see-through region of the waveguide display.

[0007] In some embodiments, at least one of the first VBG, the second VBG, or the third VBG may include a multiplexed VBG. The first VBG may include a first set of VBGs, the third VBG may include a second set of VBGs, and each VBG in the first set of VBGs and a corresponding VBG in the second set of VBGs may have a same grating vector in a plane perpendicular to a surface normal direction of the substrate and have a same grating vector or opposite grating vectors in the surface normal direction of the substrate, and may be configured to diffract the display light from a same field of view range and in a same wavelength range. In some embodiments, at least one of the first VBG, the second VBG, or the third VBG may include VBGs in two or more holographic material layers. In some embodiments, each of the second VBG and the third VBG may be characterized by a respective thickness less than 100 μm, and the waveguide display may be characterized by an angular resolution less than 2 arcminutes.

[0008] In some embodiments, the waveguide display may include a polarization convertor between two holographic material layers of the two or more holographic material layers. In some embodiments, the waveguide display may include an anti-reflection layer configured to reduce reflection of ambient light into the substrate. In some embodiments, the waveguide display may include an angular-selective transmissive layer configured to reflect, diffract, or absorb ambient light incident on the angular-selective transmissive layer with an incidence angle greater than a threshold value. In some embodiments, the waveguide display may include a light source configured to generate the display light, and projector optics configure to collimate the display light and direct the display light to the first VBG.

[0009] According to certain embodiments, a waveguide display may include a substrate transparent to visible light, a coupler configured to couple display light into the substrate as guided wave in the substrate, and a first VBG and a second VBG coupled to the substrate. The first VBG may be configured to diffract, at a first region of the first VBG, the display light in the substrate to a first direction, and diffract, at two or more regions of the first VBG along the first direction, the display light from the first region to a second direction towards the second VBG. The second VBG may be configured to couple the display light from each of the two or more regions of the first VBG out of the substrate at two or more regions of the second VBG along the second direction. Each of the first VBG and the second VBG includes a transmissive VBG or a reflective VBG. In some embodiments, the coupler may include a diffractive coupler, a refractive coupler, or a reflective coupler.

[0010] In some embodiments, the first VBG may be characterized by a thickness less than 100 μm, and the waveguide display may be characterized by an angular resolution less than 2 arcminutes. In some embodiments, the second VBG may include a transmissive VBG, and the first VBG may overlap with the second VBG in a see-through region of the waveguide display. In some embodiments, at least one of the first VBG or the second VBG may include VBGs in two or more holographic material layers. In some embodiments, at least one of the first VBG or the second VBG includes a multiplexed VBG.

[0011] This summary is neither intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this disclosure, any or all drawings, and each claim. The foregoing, together with other features and examples, will be described in more detail below in the following specification, claims, and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Illustrative embodiments are described in detail below with reference to the following figures.

[0013] FIG. **1** is a simplified block diagram of an example of an artificial reality system environment including a near-eye display system according to certain embodiments.

[0014] FIG. **2** is a perspective view of an example of a near-eye display system in the form of a head-mounted display (HMD) device for implementing some of the examples disclosed herein.

[0015] FIG. **3** is a perspective view of an example of a near-eye display system in the form of a pair of glasses for implementing some of the examples disclosed herein.

[0016] FIG. **4** is a simplified diagram illustrating an example of an optical system in a near-eye display system.

[0017] FIG. **5** illustrates an example of an optical see-through augmented reality system including a waveguide display for exit pupil expansion according to certain embodiments.

[0018] FIG. **6** illustrates an example of an optical see-through augmented reality system including a waveguide display for exit pupil expansion according to certain embodiments.

[0019] FIG. **7**A illustrates the spectral bandwidth of an example of a reflective volume Bragg grating (VBG) and the spectral bandwidth of an example of a transmissive surface-relief grating (SRG). FIG. **7**B illustrates the angular bandwidth of an example of a reflective VBG and the angular bandwidth of an example of a transmissive SRG.

[0020] FIG. **8**A illustrates an example of an optical see-through augmented reality system including a waveguide display and surface-relief gratings for exit pupil expansion according to certain embodiments. FIG. **8**B illustrates an example of an eye box including two-dimensional replicated exit pupils according to certain embodiments.

[0021] FIG. **9**A illustrates wave vectors of light diffracted by examples of surface-relief gratings for exit pupil expansion in a waveguide display and exit pupils for multiple colors.

[0022] FIG. **9**B illustrates the field-of-view clipping by the examples of surface-relief gratings for exit pupil expansion in the waveguide display.

[0023] FIG. **10**A illustrates an example of a volume Bragg grating-based waveguide display according to certain embodiments. FIG. **10**B illustrates a top view of the example of the volume Bragg grating-based waveguide display shown in FIG. **10**A. FIG. **10**C illustrates a side view of the example of the volume Bragg grating-based waveguide display shown in FIG. **10**A.

[0024] FIG. **11** illustrates light dispersion in an example of a volume Bragg grating-based waveguide display according to certain embodiments.

[0025] FIG. **12**A illustrates an example of a volume Bragg grating (VBG). FIG. **12**B illustrates the Bragg condition for the volume Bragg grating shown in FIG. **12**A.

[0026] FIG. **13**A illustrates an example of a reflective volume Bragg grating in a waveguide display according to certain embodiments. FIG. **13**B illustrates an example of a reflective VBG in a waveguide display where light diffracted by the reflective VBG is not totally reflected and guided in the waveguide. FIG. **13**C illustrates an example of a transmissive volume Bragg grating in a waveguide display according to certain embodiments. FIG. **13**D illustrates an example of a transmissive VBG in a waveguide display where light diffracted by the transmissive VBG is not totally reflected and guided in the waveguide.

[0027] FIG. **14**A illustrates the light dispersion by an example of a reflective volume Bragg grating in a waveguide display according to certain embodiments. FIG. **14**B illustrates the light dispersion by an example of a transmissive volume Bragg grating in a waveguide display according to certain embodiments.

[0028] FIG. **15**A illustrates a front view of an example of a volume Bragg grating-based waveguide display with exit pupil expansion and dispersion reduction according to certain embodiments. FIG. **15**B illustrates a side view of the example of the volume Bragg grating-based waveguide display shown in FIG. **15**A.

[0029] FIG. **16**A is a front view of an example of a volume Bragg grating-based waveguide display with exit pupil expansion and dispersion reduction according to certain embodiments.

[0030] FIG. **16**B is a side view of the example of the volume Bragg grating-based waveguide display shown in FIG. **16**A.

[0031] FIG. **17**A illustrates the propagation of light in different colors and from different fields of view in a reflective volume Bragg grating-based waveguide display according to certain embodiments. FIG. **17**B illustrates the propagation of light in different colors and from different fields of view in a transmissive volume Bragg grating-based waveguide display according to certain embodiments.

[0032] FIG. **18** illustrates an example of a reflective volume Bragg grating-based waveguide display with exit pupil expansion and dispersion reduction according to certain embodiments.

[0033] FIG. **19** illustrates an example of a transmissive volume Bragg grating-based waveguide display with exit pupil expansion and form-factor reduction according to certain embodiments.

[0034] FIG. **20** illustrates another example of a transmissive volume Bragg grating-based waveguide display according to certain embodiments.

[0035] FIG. **21** illustrates an example of a volume Bragg grating-based waveguide display with exit pupil expansion, dispersion reduction, and form-factor reduction according to certain embodiments.

[0036] FIG. **22**A illustrates another example of a volume Bragg grating-based waveguide display with exit pupil expansion, dispersion reduction, form-factor reduction, and power efficiency improvement according to certain embodiments. FIG. **22**B illustrates examples of replicated exit pupils at an eyebox of the volume Bragg grating-based waveguide display shown in FIG. **22**A.

[0037] FIG. **23**A illustrates an example of a volume Bragg grating-based waveguide display with exit pupil expansion, dispersion reduction, and form-factor reduction according to certain embodiments. FIG. **23**B illustrates an example of a volume Bragg grating-based waveguide display with exit pupil expansion, dispersion reduction, form-factor reduction, and power efficiency improvement according to certain embodiments.

[0038] FIG. **24**A is a front view of an example of a volume Bragg grating-based waveguide display including an image projector and multiple polymer layers according to certain embodiments. FIG. **24**B is a side view of the example of the volume Bragg grating-based waveguide display including the image projector and multiple polymer layers according to certain embodiments.

[0039] FIG. **25** illustrates an example of a volume Bragg grating-based waveguide display including multiple grating layers for different fields of view and/or light wavelengths according to certain embodiments.

[0040] FIG. **26** illustrates an example of a waveguide display including two multiplexed volume Bragg gratings and a polarization convertor between the two multiplexed volume Bragg gratings according to certain embodiments.

[0041] FIG. **27** illustrates an example of a waveguide display including an anti-reflection layer and an angular-selective transmissive layer according to certain embodiments.

[0042] FIG. **28** is a simplified block diagram of an example electronic system of an example near-eye display according to certain embodiments.

[0043] The figures depict embodiments of the present disclosure for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated may be employed without departing from the principles, or benefits touted, of this disclosure.

[0044] In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

DETAILED DESCRIPTION

[0045] This disclosure relates generally to volume Bragg grating (VBG)-based waveguide display for near-eye display systems. In a near-eye display system, it is generally desirable to expand the eyebox, reduce display haze, improve image quality (e.g., resolution and contrast), reduce physical size, increase power efficiency, and increase the field of view. In a waveguide-based near-eye display system, light of projected images may be coupled into a waveguide (e.g., a transparent substrate), propagate within the waveguide, and be coupled out of the waveguide at different locations to replicate exit pupils and expand the eyebox. Two or more gratings may be used to expand the exit pupil in two dimensions. In a waveguide-based near-eye display system for augmented reality applications, light from the surrounding environment may pass through at least a see-through region of the waveguide display (e.g., the transparent substrate) and reach the user's eyes. In some implementations, the light of the projected images may be coupled into or out of the waveguide using diffractive optical elements, such as gratings. Couplers implemented using diffractive optical elements may cause dispersion between light of different colors due to the wavelength dependency of light diffraction. Therefore, images of different color components in a color image may not overlap and thus the resolution of the displayed image may be reduced. To reduce the dispersion and improve the resolution, thick transmissive and/or reflective VBG gratings may be used, which may be impractical in many cases and/or may cause significant display haze. For example, in some cases, transmissive VBG gratings with a thickness of greater than 1 mm may be used to achieve a desired resolution performance. Reflective VBG gratings with a lower thickness may be used to achieve the desired resolution performance. However, with reflection gratings, the gratings for two-dimensional pupil expansion may not overlap and thus the physical size of the waveguide display may be large.

[0046] According to certain embodiments, two VBG gratings (or two portions of a same grating) with matching grating vectors (e.g., having the same grating vector in a plane perpendicular to a surface normal direction of the transparent substrate and having the same and/or opposite grating vectors in the surface-normal direction of the transparent substrate, but recorded in different exposure durations to achieve different diffraction efficiencies) may be used to diffract display light and expand the exit pupil in one dimension. The two VBG gratings may compensate for the dispersion of display light caused by each other to reduce the overall dispersion, due to the opposite Bragg conditions (e.g., +1 order and −1 order diffractions) at the two VBG gratings. Therefore, thin VBG gratings may be used to achieve the desired resolution. Because of the dispersion compensation, thin transmissive VBG gratings may be used to achieve the desired resolution, and the gratings for the two-dimensional pupil expansion may at least partially overlap to reduce the physical size of the waveguide display.

[0047] In some embodiments, a first pair of VBG gratings (or two portions of a grating) may be used to expand the exit pupil in one dimension and compensate for the dispersion caused by each other, and a second pair of VBG gratings (or two portions of a grating) may be used to expand the exit pupil in another dimension and may compensate for the dispersion caused by each other. Thus, the exit pupil may be replicated in two dimensions and the resolution of the displayed images may be high in both dimensions.

[0048] In the following description, various inventive embodiments are described, including devices, systems, methods, and the like. For the purposes of explanation, specific details are set forth in order to provide a thorough understanding of examples of the disclosure. However, it will be apparent that various examples may be practiced without these specific details. For example, devices, systems, structures, assemblies, methods, and other components may be shown as components in block diagram form in order not to obscure the examples in unnecessary detail. In other instances, well-known devices, processes, systems, structures, and techniques may be shown without necessary detail in order to avoid obscuring the examples. The figures and description are not intended to be restrictive. The terms and expressions that have been employed in this disclosure are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof. The word "example" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or design described herein as "example" is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[0049] FIG. **1** is a simplified block diagram of an example of an artificial reality system environment **100** including a near-eye display **120** in accordance with certain embodiments. Artificial reality system environment **100** shown in FIG. **1** may include near-eye display **120**, an optional external imaging device **150**, and an optional input/output interface **140**, each of which may be coupled to an optional console **110**. While FIG. **1** shows an example of artificial reality system environment **100** including one near-eye display **120**, one external imaging device **150**, and one input/output interface **140**, any number of these components may be included in artificial reality system environment **100**, or any of the components may be omitted. For example, there may be multiple near-eye displays **120** monitored by one or more external imaging devices **150** in communication with console **110**. In some configurations, artificial reality system environment **100** may not include external imaging device **150**, optional input/output interface **140**, and optional console **110**. In alternative configurations, different or additional components may be included in artificial reality system environment **100**.

[0050] Near-eye display **120** may be a head-mounted display that presents content to a user. Examples of content presented by near-eye display **120** include one or more of images, videos, audio, or any combination thereof. In some embodiments, audio may be presented via an external device (e.g., speakers and/or headphones) that receives audio information from near-eye display **120**, console **110**, or both, and presents audio data based on the audio information. Near-eye display **120** may include one or more rigid bodies, which may be rigidly or non-rigidly coupled to each other. A rigid coupling between rigid bodies may cause the coupled rigid bodies to act as a single rigid entity. A non-rigid coupling between rigid bodies may allow the rigid bodies to move relative to each other. In various embodiments, near-eye display **120** may be implemented in any suitable form-factor, including a pair of glasses. Some embodiments of near-eye display **120** are further described below with respect to FIGS. **2** and **3**. Additionally, in various embodiments, the functionality described herein may be used in a headset that combines images of an environment external to near-eye display **120** and artificial reality content (e.g., computer-generated images). Therefore, near-eye display **120** may augment images of a physical, real-world environment external to near-eye display **120** with generated content (e.g., images, video, sound, etc.) to present an augmented reality to a user.

[0051] In various embodiments, near-eye display **120** may include one or more of display electronics **122**, display optics **124**, and an eye-tracking unit **130**. In some embodiments, near-eye display **120** may also include one or more locators **126**, one or more position sensors **128**, and an inertial measurement unit (IMU) **132**. Near-eye display **120** may omit any of eye-tracking unit **130**, locators **126**, position sensors **128**, and IMU **132**, or include additional elements in various embodiments. Additionally, in some embodiments, near-eye display **120** may include elements combining the function of various elements described in conjunction with FIG. **1**.

[0052] Display electronics **122** may display or facilitate the display of images to the user according to data received from, for example, console **110**. In various embodiments, display electronics **122** may include one or more display panels, such as a liquid crystal display (LCD), an organic light emitting diode (OLED) display, an inorganic light emitting diode (ILED) display, a micro light emitting diode (μLED) display, an active-matrix OLED display (AMOLED), a transparent OLED display (TOLED), or some other display. For example, in one implementation of near-eye display **120**, display electronics **122** may include a front TOLED panel, a rear display panel, and an optical component (e.g., an attenuator, polarizer, or diffractive or spectral film) between the front and rear display panels. Display electronics **122** may include pixels to emit light of a predominant color such as red, green, blue, white, or yellow. In some implementations, display electronics **122** may display a three-dimensional (3D) image through stereoscopic effects produced by two-dimensional panels to create a subjective perception of image depth. For example, display electronics **122** may include a left display and a right display positioned in front of a user's left eye and right eye, respectively. The left and right displays may present copies of an image shifted horizontally relative to each other to create a stereoscopic effect (e.g., a perception of image depth by a user viewing the image).

[0053] In certain embodiments, display optics **124** may display image content optically (e.g., using optical waveguides and couplers) or magnify image light received from display electronics **122**, correct optical errors associated with the image light, and present the corrected image light to a user of near-eye display **120**. In various embodiments, display optics **124** may include one or more optical elements, such as, for example, a substrate, optical waveguides, an aperture, a Fresnel lens, a convex lens, a concave lens, a filter, input/output couplers, or any other suitable optical elements that may affect image light emitted from display electronics **122**. Display optics **124** may include a combination of different optical elements as well as mechanical couplings to maintain relative spacing and orientation of the optical elements in the combination. One or more optical elements in display optics **124** may have an optical coating, such as an anti-reflective coating, a reflective coating, a filtering coating, or a combination of different optical coatings.

[0054] Magnification of the image light by display optics **124** may allow display electronics **122** to be physically smaller, weigh less, and consume less power than larger displays. Additionally, magnification may increase a field of view of the displayed content. The amount of magnification of image light by display optics **124** may be changed by adjusting, adding, or removing optical elements from display optics **124**. In some embodiments, display optics **124** may project displayed images to one or more image planes that may be further away from the user's eyes than near-eye display **120**.

[0055] Display optics **124** may also be designed to correct one or more types of optical errors, such as two-dimensional optical errors, three-dimensional optical errors, or any combination thereof. Two-dimensional errors may include optical aberrations that occur in two dimensions. Example types of two-dimensional errors may include barrel distortion, pincushion distortion, longitudinal chromatic aberration, and transverse chromatic aberration. Three-dimensional errors may include optical errors that occur in three dimensions. Example types of three-dimensional errors may include spherical aberration, comatic aberration, field curvature, and astigmatism.

[0056] Locators **126** may be objects located in specific positions on near-eye display **120** relative to one another and relative to a reference point on near-eye display **120**. In some implementations, console **110** may identify locators **126** in images captured by external imaging device **150** to determine the artificial reality headset's position, orientation, or both. A locator **126** may be an LED, a corner cube reflector, a reflective marker, a type of light source that contrasts with an environment in which near-eye display **120** operates, or any combination thereof. In embodiments where locators **126** are active components (e.g., LEDs or other types of light emitting devices), locators **126** may emit light in the visible band (e.g., about 380 nm to 750 nm), in the infrared (IR) band (e.g., about 750 nm to 1 mm), in the ultraviolet band (e.g., about 10 nm to about 380 nm), in another portion of the electromagnetic spectrum, or in any combination of portions of the electromagnetic spectrum.

[0057] External imaging device **150** may include one or more cameras, one or more video cameras, any other device capable of capturing images including one or more of locators **126**, or any combination thereof. Additionally, external imaging device **150** may include one or more filters (e.g., to increase signal to noise ratio). External imaging device **150** may be configured to detect light emitted or reflected from locators **126** in a field of view of external imaging device **150**. In embodiments where locators **126** include passive elements (e.g., retroreflectors), external imaging device **150** may include a light source that illuminates some or all of locators **126**, which may retro-reflect the light to the light source in external imaging device **150**. Slow calibration data may be communicated from external imaging device **150** to console **110**, and external imaging device **150** may receive one or more calibration parameters from console **110** to adjust one or more imaging parameters (e.g., focal length, focus, frame rate, sensor temperature, shutter speed, aperture, etc.).

[0058] Position sensors **128** may generate one or more measurement signals in response to motion of near-eye display **120**. Examples of position sensors **128** may include accelerometers, gyroscopes, magnetometers, other motion-detecting or error-correcting sensors, or any combination thereof. For example, in some embodiments, position sensors **128** may include multiple accelerometers to measure translational motion (e.g., forward/back, up/down, or left/right) and multiple gyroscopes to measure rotational motion (e.g., pitch, yaw, or roll). In some embodiments, various position sensors may be oriented orthogonally to each other.

[0059] IMU **132** may be an electronic device that generates fast calibration data based on measurement signals received from one or more of position sensors **128**. Position sensors **128** may be located external to IMU **132**, internal to IMU **132**, or any combination thereof. Based on the one or more measurement signals from one or more position sensors **128**, IMU **132** may generate fast calibration data indicating an estimated position of near-eye display **120** relative to an initial position of near-eye display **120**. For example, IMU **132** may integrate measurement signals received from accelerometers over time to estimate a velocity vector and integrate the velocity vector over time to determine an estimated position of a reference point on near-eye display **120**. Alternatively, IMU **132** may provide the sampled measurement signals to console **110**, which may determine the fast calibration data. While the reference point may generally be defined as a point in space, in various embodiments, the reference point may also be defined as a point within near-eye display **120** (e.g., a center of IMU **132**).

[0060] Eye-tracking unit **130** may include one or more eye-tracking systems. Eye tracking may refer to determining an eye's position, including orientation and location of the eye, relative to near-eye display **120**. An eye-tracking system may include an imaging system to image one or more eyes and may optionally include a light emitter, which may generate light that is directed to an eye such that light reflected by the eye may be captured by the imaging system. For example, eye-tracking unit **130** may include a non-coherent or coherent light source (e.g., a laser diode) emitting light in the visible spectrum or infrared spectrum, and a camera capturing the light reflected by the user's eye. As another example, eye-tracking unit **130** may capture reflected radio waves emitted by a miniature radar unit. Eye-tracking unit **130** may use low-power light emitters that emit light at frequencies and intensities that would not injure the eye or cause physical discomfort. Eye-tracking unit **130** may be arranged to increase contrast in images of an eye captured by eye-tracking unit **130** while reducing the overall power consumed by eye-tracking unit **130** (e.g., reducing power consumed by a light emitter and an imaging system included in eye-tracking unit **130**). For example, in some implementations, eye-tracking unit **130** may consume less than 100 milliwatts of power.

[0061] Near-eye display **120** may use the orientation of the eye to, e.g., determine an inter-pupillary distance (IPD) of the user, determine gaze direction, introduce depth cues (e.g., blur image outside of the user's main line of sight), collect heuristics on the user interaction in the VR media (e.g., time spent on any particular subject, object, or frame as a function of exposed stimuli), some other functions that are based in part on the orientation of at least one of the user's eyes, or any combination thereof. Because the orientation may be determined for both eyes of the user, eye-tracking unit **130** may be able to determine where the user is looking. For example, determining a direction of a user's gaze may include determining a point of convergence based on the determined orientations of the user's left and right eyes. A point of convergence may be the point where the two foveal axes of the user's eyes intersect. The direction of the user's gaze may be the direction of a line passing through the point of convergence and the mid-point between the pupils of the user's eyes.

[0062] Input/output interface **140** may be a device that allows a user to send action requests to console **110**. An action request may be a request to perform a particular action. For example, an action request may be to start or to end an application or to perform a particular action within the application. Input/output interface **140** may include one or more input devices. Example input devices may include a keyboard, a mouse, a game controller, a glove, a button, a touch screen, or any other suitable device for receiving action requests and communicating the received action requests to console **110**. An action request received by the input/output interface **140** may be communicated to console **110**, which may perform an action corresponding to the requested action. In some embodiments, input/output interface **140** may provide haptic feedback to the user in accordance with instructions received from console **110**. For example, input/output interface **140** may provide haptic feedback when an action request is received, or when console **110** has performed a requested action and communicates instructions to input/output interface **140**. In some embodiments, external imaging device **150** may be used to track input/output interface **140**, such as tracking the location or position of a controller (which may include, for example, an IR light source) or a hand of the user to determine the motion of the user. In some embodiments, near-eye display **120** may include one or more imaging devices to track input/output interface **140**, such as tracking the location or position of a controller or a hand of the user to determine the motion of the user.

[0063] Console **110** may provide content to near-eye display **120** for presentation to the user in accordance with information received from one or more of external imaging device **150**, near-eye display **120**, and input/output interface **140**. In the example shown in FIG. **1**, console **110** may include an application store **112**, a headset tracking module **114**, an artificial reality engine **116**, and an eye-tracking module **118**. Some embodiments of console **110** may include different or additional modules than those described in conjunction with FIG. **1**. Functions further described below may be distributed among components of console **110** in a different manner than is described here.

[0064] In some embodiments, console **110** may include a processor and a non-transitory computer-readable storage medium storing instructions executable by the processor. The processor may include multiple processing units executing instructions in parallel. The non-transitory computer-readable storage medium may be any memory, such as a hard disk drive, a removable memory, or a solid-state drive (e.g., flash memory or dynamic random access memory (DRAM)). In various embodiments, the modules of console **110** described in conjunction with FIG. **1** may be encoded as instructions in the non-transitory computer-readable storage medium that, when executed by the processor, cause the processor to perform the functions further described below.

[0065] Application store **112** may store one or more applications for execution by console **110**. An application may include a group of instructions that, when executed by a processor, generates content for presentation to the user. Content generated by an application may be in response to inputs received from the user via movement of the user's eyes or inputs received from the input/output interface **140**. Examples of the applications may include gaming applications, conferencing applications, video playback application, or other suitable applications.

[0066] Headset tracking module **114** may track movements of near-eye display **120** using slow calibration information from external imaging device **150**. For example, headset tracking module **114** may determine positions of a reference point of near-eye display **120** using observed locators from the slow calibration information and a model of near-eye display **120**. Headset tracking module **114** may also determine positions of a reference point of near-eye display **120** using position information from the fast calibration information. Additionally, in some embodiments, headset tracking module **114** may use portions of the fast calibration information, the slow calibration information, or any combination thereof, to predict a future location of near-eye display **120**. Headset tracking module **114** may provide the estimated or predicted future position of near-eye display **120** to artificial reality engine **116**.

[0067] Artificial reality engine **116** may execute applications within artificial reality system environment **100** and receive position information of near-eye display **120**, acceleration information of near-eye display **120**, velocity information of near-eye display **120**, predicted future positions of near-eye display **120**, or any combination thereof from headset tracking module **114**. Virtual reality engine **116** may also receive estimated eye position and orientation information from eye-tracking module **118**. Based on the received information, artificial reality engine **116** may determine content to provide to near-eye display **120** for presentation to the user. For example, if the received information indicates that the user has looked to the left, artificial reality engine **116** may generate content for near-eye display **120** that mirrors the user's eye movement in a virtual environment. Additionally, artificial reality engine **116** may perform an action within an application executing on console **110** in response to an action request received from input/output interface **140**, and provide feedback to the user indicating that the action has been performed. The feedback may be visual or audible feedback via near-eye display **120** or haptic feedback via input/output interface **140**.

[0068] Eye-tracking module **118** may receive eye-tracking data from eye-tracking unit **130** and determine the position of the user's eye based on the eye tracking data. The position of the eye may include an eye's orientation, location, or both relative to near-eye display **120** or any element thereof. Because the eye's axes of rotation change as a function of the eye's location in its socket, determining the eye's location in its socket may allow eye-tracking module **118** to more accurately determine the eye's orientation.

[0069] FIG. **2** is a perspective view of an example of a near-eye display in the form of an HMD device **200** for implementing some of the examples disclosed herein. HMD device **200** may be a part of, e.g., a VR system, an AR system, an MR system, or any combination thereof. HMD device **200** may include a body **220** and a head strap **230**. FIG. **2** shows a top side **223**, a front side **225**, and a right side **227** of body **220** in the perspective view. Head strap **230** may have an adjustable or extendible length. There may be a sufficient space between body **220** and head strap **230** of HMD device **200** for allowing a user to mount HMD device **200** onto the user's head. In various embodiments, HMD device **200** may include additional, fewer, or different components. For example, in some embodiments, HMD device **200** may include eyeglass temples and temple tips as shown in, for example, FIG. **3** below, rather than head strap **230**.

[0070] HMD device **200** may present to a user media including virtual and/or augmented views of a physical, real-world environment with computer-generated elements. Examples of the media presented by HMD device **200** may include images (e.g., two-dimensional (2D) or three-dimensional (3D) images), videos (e.g., 2D or 3D videos), audio, or any combination thereof. The images and videos may be presented to each eye of the user by one or more display assemblies (not shown in FIG. **2**) enclosed in body **220** of HMD device **200**. In various embodiments, the one or more display assemblies may include a single electronic display panel or multiple electronic display panels (e.g., one display panel for each eye of the user). Examples of the electronic display panel(s) may include, for example, an LCD, an OLED display, an ILED display, a μLED display, an AMOLED, a TOLED, some other display, or any combination thereof. HMD device **200** may include two eyebox regions.

[0071] In some implementations, HMD device **200** may include various sensors (not shown), such as depth sensors, motion sensors, position sensors, and eye tracking sensors. Some of these sensors may use a structured light pattern for sensing. In some implementations, HMD device **200** may include an input/output interface for communicating with a console. In some implementations, HMD device **200** may include a virtual reality engine (not shown) that can execute applications within HMD device **200** and receive depth information, position information, acceleration information, velocity information, predicted future positions, or any combination thereof of HMD device **200** from the various sensors. In some implementations, the information received by the virtual reality engine may be used for producing a signal (e.g., display instructions) to the one or more display assemblies. In some implementations, HMD device **200** may include locators (not shown, such as locators **126**) located in fixed positions on body **220** relative to one another and relative to a reference point. Each of the locators may emit light that is detectable by an external imaging device.

[0072] FIG. **3** is a perspective view of an example of a near-eye display **300** in the form of a pair of glasses for implementing some of the examples disclosed herein. Near-eye display **300** may be a specific implementation of near-eye display **120** of FIG. **1**, and may be configured to operate as a virtual reality display, an augmented reality display, and/or a mixed reality display. Near-eye display **300** may include a frame **305** and a display **310**. Display **310** may be configured to present content to a user. In some embodiments, display **310** may include display electronics and/or display optics. For example, as described above with respect to near-eye display **120** of FIG. **1**, display **310** may include an LCD display panel, an LED display panel, or an optical display panel (e.g., a waveguide display assembly).

[0073] Near-eye display **300** may further include various sensors **350*a***, **350*b***, **350*c***, **350*d***, and **350*e*** on or within frame **305**. In some embodiments, sensors **350*a*-350*e*** may include one or more depth sensors, motion sensors, position sensors, inertial sensors, or ambient light sensors. In some embodiments, sensors **350*a*-350*e*** may include one or more image sensors configured to generate image data representing different fields of views in different directions. In some embodiments, sensors **350*a*-350*e*** may be used as input devices to control or influence the displayed content of near-eye display **300**, and/or to provide an interactive VR/AR/MR experience to a user of near-eye display **300**. In some embodiments, sensors **350*a*-350*e*** may also be used for stereoscopic imaging.

[0074] In some embodiments, near-eye display **300** may further include one or more illuminators **330** to project light into the physical environment. The projected light may be associated with different frequency bands (e.g., visible light, infra-red light, ultra-violet light, etc.), and may serve various purposes. For example, illuminator(s) **330** may project light in a dark environment (or in an environment with low intensity of infra-red light, ultra-violet light, etc.) to assist sensors **350*a*-350*e*** in capturing images of different objects within the dark environment. In some embodiments, illuminator(s) **330** may be used to project certain light pattern onto the objects within the environment. In some embodiments, illuminator(s) **330** may be used as locators, such as locators **126** described above with respect to FIG. **1**.

[0075] In some embodiments, near-eye display **300** may also include a high-resolution camera **340**. Camera **340** may capture images of the physical environment in the field of view. The captured images may be processed, for example, by a virtual reality engine (e.g., artificial reality engine **116** of FIG. **1**) to add virtual objects to the captured images or modify physical objects in the captured images, and the processed images may be displayed to the user by display **310** for AR or MR applications.

[0076] FIG. **4** is a simplified diagram illustrating an example of an optical system **400** in a near-eye display system. Optical system **400** may include an image source **410** and projector optics **420**. In the example shown in FIG. **4**, image source **410** is in front of projector optics **420**. In various embodiments, image source **410** may be located outside of the field of view of user's eye **490**. For example, one or more reflectors or directional couplers may be used to deflect light from an image source that is outside of the field of view of user's eye **490** to make the image source appear to be at the location of image source **410** shown in FIG. **4**. Light from an area (e.g., a pixel or a light emitting device) on image source **410** may be collimated and directed to an exit pupil **430** by projector optics **420**. Thus, objects at different spatial locations on image source **410** may appear to be objects far away from user's eye **490** in different viewing angles (FOVs). The collimated light from different viewing angles may then be focused by the lens of user's eye **490** onto different locations on retina **492** of user's eye **490**. For example, at least some portions of the light may be focused on a fovea **494** on retina **492**. Collimated light rays from an area on image source **410** and incident on user's eye **490** from a same direction may be focused onto a same location on retina **492**. As such, a single image of image source **410** may be formed on retina **492**.

[0077] The user experience of using an artificial reality system may depend on several characteristics of the optical system, including field of view (FOV), image quality (e.g., angular resolution), size of the eyebox (to accommodate for eye and head movements), and brightness of the light (or contrast) within the eyebox. Field of view describes the angular range of the image as seen by the user, usually measured in degrees as observed by one eye (for a monocular HMD) or both eyes (for either biocular or binocular HMDs). The human visual system may have a total binocular FOV of about 200° (horizontal) by 130° (vertical). To create a fully immersive visual environment, a large FOV is desirable because a large FOV (e.g., greater than about 60°) may provide a sense of "being in" an image, rather than merely viewing the image. Smaller fields of view may also preclude some important visual information. For example, an HMD system with a small FOV may use a gesture interface, but the users may not see their hands in the small FOV to be sure that they are using the correct motions. On the other hand, wider fields of view may require larger displays or optical systems, which may influence the size, weight, cost, and comfort of using the HMD.

[0078] Resolution may refer to the angular size of a displayed pixel or image element appearing to a user, or the ability for the user to view and correctly interpret an object as imaged by a pixel and/or other pixels. The resolution of an HMD may be specified as the number of pixels on the image source for a given FOV value, from which an angular resolution may be determined by dividing the FOV in one direction by the number of pixels in the same direction on the image source. For example, for a horizontal FOV of 40° and 1080 pixels in the horizontal direction on the image source, the corresponding angular resolution may be about 2.2 arc-minutes, compared with the one-arc-minute resolution associated with Snellen 20/20 human visual acuity.

[0079] In some cases, the eyebox may be a two-dimensional box in front of the user's eye, from which the displayed image from the image source may be viewed. If the pupil of the user moves outside of the eyebox, the displayed image may not be seen by the user. For example, in a non-pupil-forming configuration, there exists a viewing eyebox within which there will be unvignetted viewing of the HMD image source, and the displayed image may vignette or may be clipped but may still be viewable when the pupil of user's eye is outside of the viewing eyebox. In a pupil-forming configuration, the image may not be viewable outside the exit pupil.

[0080] The fovea of a human eye, where the highest resolution may be achieved on the retina, may correspond to an FOV of about 2° to about 3°. This may require that the eye rotates in order to view off-axis objects with a highest resolution. The rotation of the eye to view the off-axis objects may introduce a translation of the pupil because the eye rotates around a point that is about 10 mm behind the pupil. In addition, a user may not always be able to accurately position the pupil (e.g., having a radius of about 2.5 mm) of the user's eye at an ideal location in the eyebox. Furthermore, the environment where the HMD is used may require the eyebox to be larger to allow for movement of the user's eye and/or head relative the HMD, for example, when the HMD is used in a moving vehicle or designed to be used while the user is moving on foot. The amount of movement in these situations may depend on how well the HMD is coupled to the user's head.

[0081] Thus, the optical system of the HMD may need to provide a sufficiently large exit pupil or viewing eyebox for viewing the full FOV with full resolution, in order to accommodate the movements of the user's pupil relative to the HMD. For example, in a pupil-forming configuration, a minimum size of 12 mm to 15 mm may be desired for the exit pupil. If the eyebox is too small, minor misalignments between the eye and the HMD may result in at least partial loss of the image, and the user experience may be substantially impaired. In general, the lateral extent of the eyebox is more critical than the vertical extent of the eyebox. This may be in part due to the significant variances in eye separation distance between users, and the fact that misalignments to eyewear tend to more frequently occur in the lateral dimension and users tend to more frequently adjust their gaze left and right, and with greater amplitude, than adjusting the gaze up and down. Thus, techniques that can increase the lateral dimension of the eyebox may substantially improve a user's experience with an HMD. On the other hand, the larger the eyebox, the larger the optics and the heavier and bulkier the near-eye display device may be.

[0082] In order to view the displayed image against a bright background, the image source of an AR HMD may need to be sufficiently bright, and the optical system may need to be efficient to provide a bright image to the user's eye such that the displayed image may be visible in a background including strong ambient light, such as sunlight. The optical system of an HMD may be designed to concentrate light in the eyebox. When the eyebox is large, an image source with high power may be used to provide a bright image viewable within the large eyebox. Thus, there may be trade-offs among the size of the eyebox, cost, brightness, optical complexity, image quality, and size and weight of the optical system.

[0083] FIG. **5** illustrates an example of an optical see-through augmented reality system **500** including a waveguide display for exit pupil expansion according to certain embodiments. Augmented reality system **500** may include a projector **510** and a combiner **515**. Projector **510** may include a light source or image source **512** and projector optics **514**. In some embodiments, light source or image source **512** may include one or more micro-LED devices. In some embodiments, image source **512** may include a plurality of pixels that displays virtual objects, such as an LCD display panel or an LED display panel. In some embodiments, image source **512** may include a light source that generates coherent or partially coherent light. For example, image source **512** may include a laser diode, a vertical cavity surface emitting laser, an LED, a superluminescent LED (sLED), and/or a micro-LED described above. In some embodiments, image source **512** may include a plurality of light sources (e.g., an array of micro-LEDs described above) each emitting a monochromatic image light corresponding to a primary color (e.g., red, green, or blue). In some embodiments, image source **512** may include three two-dimensional arrays of micro-LEDs, where each two-dimensional array of micro-LEDs may include micro-LEDs configured to emit light of a primary color (e.g., red, green, or blue). In some embodiments, image source **512** may include an optical pattern generator, such as a spatial light modulator. Projector optics **514** may include one or more optical components that can condition the light from image source **512**, such as expanding, collimating, scanning, or projecting light from image source **512** to combiner **515**. The one or more optical components may include, for example, one or more lenses, liquid lenses, mirrors, free-form optics, apertures, and/or gratings. For example, in some embodiments, image source **512** may include one or more one-dimensional arrays or elongated two-dimensional arrays of micro-LEDs, and projector optics **514** may include one or more one-dimensional scanners (e.g., micro-mirrors or prisms) configured to scan the one-dimensional arrays or elongated two-dimensional arrays of micro-LEDs to generate image frames. In some embodiments, projector optics **514** may include a liquid lens (e.g., a liquid crystal lens) with a plurality of electrodes that allows scanning of the light from image source **512**.

[0084] Combiner **515** may include an input coupler **530** for coupling light from projector **510** into a substrate **520** of combiner **515**. Input coupler **530** may include a volume holographic grating or another diffractive optical element (DOE) (e.g., a surface-relief grating (SRG)), a slanted reflective surface of substrate **520**, or a refractive coupler (e.g., a wedge or a prism). Input coupler **530** may have a coupling efficiency of greater than 30%, 50%, 75%, 90%, or higher for visible light. Visible light coupled into substrate **520** may propagate within substrate **520** through, for example, total internal reflection (TIR). Substrate **520** may be in the form of a lens of a pair of eyeglasses. Substrate **520** may have a flat or a curved surface, and may include one or more types of dielectric materials, such as glass, quartz, plastic, polymer, poly(methyl methacrylate) (PMMA), crystal, ceramic, or the like. A thickness of the substrate may range from, for example, less than about 1 mm to about 10 mm or more. Substrate **520** may be transparent to visible light.

[0085] Substrate **520** may include or may be coupled to a plurality of output couplers **540** each configured to extract at least a portion of the light guided by and propagating within substrate **520** from substrate **520**, and direct extracted light **560** to an eyebox **595** where an eye **590** of the user of augmented reality system **500** may be located when augmented reality system **500** is in use. The plurality of output couplers **540** may replicate the exit pupil to increase the size of eyebox **595**, such that the displayed image may be visible in a larger area. As input coupler **530**, output couplers **540** may include grating couplers (e.g., volume holographic gratings or surface-relief gratings), other diffraction optical elements (DOEs), prisms, etc. Output couplers **540** may have different coupling (e.g., diffraction) efficiencies at different locations. Substrate **520** may also allow light **550** from the environment in front of combiner **515** to pass through with little or no loss. Output couplers **540** may also allow light **550** to pass through with little loss. For example, in some implementations, output couplers **540** may have a very low diffraction efficiency for light **550** such that light **550** may be refracted or otherwise pass through output couplers **540** with little loss, and thus may have a higher intensity than extracted light **560**. As a result, the user may be able to view combined images of the environment in front of combiner **515** and images of virtual objects projected by projector **510**. In some implementations, output couplers **540** may have a high diffraction efficiency for light **550** and may diffract light **550** to certain desired directions (e.g., diffraction angles) with little loss.

[0086] In some embodiments, projector **510**, input coupler **530**, and output coupler **540** may be on any side of substrate **520**. Input coupler **530** and output coupler **540** may be reflective gratings (also referred to as reflection gratings) or transmissive gratings (also referred to as transmission gratings) to couple display light into or out of substrate **520**.

[0087] FIG. **6** illustrates an example of an optical see-through augmented reality system **600** including a waveguide display for exit pupil expansion according to certain embodiments. Augmented reality system **600** may be similar to augmented reality system **500**, and may include the waveguide display and a projector that may include a light source or image source **612** and projector optics **614**. The waveguide display may include a substrate **630**, an input coupler **640**, and a plurality of output couplers **650** as described above with respect to augmented reality system **500**. While FIG. **5** only shows the propagation of light from a single field of view, FIG. **6** shows the propagation of light from multiple fields of view.

[0088] FIG. **6** shows that the exit pupil is replicated by output couplers **650** to form an aggregated exit pupil or eyebox, where different fields of view (e.g., different pixels on image source **612**) may be associated with different respective propagation directions towards the eyebox, and light from a same field of view (e.g., a same pixel on image source **612**) may have a same propagation direction for the different individual exit pupils. Thus, a single image of image source **612** may be formed by the user's eye located anywhere in the eyebox, where light from different individual exit pupils and propagating in the same direction may be from a same pixel on image source **612** and may be focused onto a same location on the retina of the user's eye. FIG. **6** shows that the image of the image source is visible by the user's eye even if the user's eye moves to different locations in the eyebox.

[0089] In many waveguide-based near-eye display systems, in order to expand the eyebox of the waveguide-based near-eye display in two dimensions, two or more output gratings may be used to expand the display light in two dimensions or along two axes (which may be referred to as dual-axis pupil expansion). The two gratings may have different grating parameters, such that one grating may be used to replicate the exit pupil in one direction and the other grating may be used to replicate the exit pupil in another direction.

[0090] As described above, the input and output grating couplers described above can be volume holographic gratings or surface-relief gratings, which may have very different Klein-Cook parameter Q:

$$Q = \frac{2\pi\lambda d}{n\Lambda^2},$$

where d is the thickness of the grating, λ is the wavelength of the incident light in free space, Λ is the grating period, and n is the refractive index of the recording medium. The Klein-Cook parameter Q may divide light diffraction by gratings into three regimes. When a grating is characterized by $Q \ll 1$, light diffraction by the grating may be referred to as Raman-Nath diffraction, where multiple diffraction orders may occur for normal and/or oblique incident light. When a grating is characterized by $Q \gg 1$ (e.g., $Q \geq 10$), light diffraction by the grating may be referred to as Bragg diffraction, where generally only the zeroth and the ±1 diffraction orders may occur for light incident on the grating at an angle satisfying the Bragg condition. When a grating is characterized by $Q \sim 1$, the diffraction by the grating may be between the Raman-Nath diffraction and the Bragg diffraction. To meet Bragg conditions, the thickness d of the grating may be higher than certain values to occupy a volume (rather than at a surface) of a medium, and thus may be referred to as a volume Bragg grating. VBGs may generally have relatively small refractive index modulations (e.g., $\Delta n \leq 0.05$) and high spectral and angular selectivity, while surface-relief gratings may generally have large refractive index modulations (e.g., $\Delta n \geq 0.5$) and wide spectral and angular bandwidths.

[0091] FIG. **7**A illustrates the spectral bandwidth of an example of a volume Bragg grating (e.g., a reflective VBG) and the spectral bandwidth of an example of a surface-relief grating (e.g., a transmissive SRG). The horizontal axis represents the wavelength of the incident visible light and the vertical axis corresponds to the diffraction efficiency. As shown by a curve **710**, the diffraction efficiency of the reflective VBG is high in a narrow wavelength range, such as green light. In contrast, the diffraction efficiency of the transmissive SRG may be high in a very wide wavelength range, such as from blue to red light, as shown by a curve **720**.

[0092] FIG. **7**B illustrates the angular bandwidth of an example of a volume Bragg grating (e.g., a reflective VBG) and the angular bandwidth of an example of a surface-relief grating (e.g., a transmissive SRG). The horizontal axis represents the incident angle of the visible light incident on the grating, and the vertical axis corresponds to the diffraction efficiency. As shown by a curve **715**, the diffraction efficiency of the reflective VBG is high for light incident on the grating from a narrow angular range, such as about ±2.5° from the perfect Bragg condition. In contrast, the diffraction efficiency of the transmissive SRG is high in a very wide angular range, such as greater than about ±10° or wider, as shown by a curve **725**.

[0093] Due to the high spectral selectivity at the Bragg condition, VBGs, such as reflective VBGs, may allow for single-waveguide design without crosstalk between primary colors, and may exhibit superior see-through quality. However, the spectral and angular selectivity may lead to lower efficiency because only a portion of the display light in the full FOV may be diffracted and reach user's eyes.

[0094] FIG. **8**A illustrates an example of an optical see-through augmented reality system including a waveguide display **800** and surface-relief gratings for exit pupil expansion according to certain embodiments. Waveguide display **800** may include a substrate **810** (e.g., a waveguide), which may be similar to substrate **520**. Substrate **810** may be transparent to visible light and may include, for example, a glass, quartz, plastic, polymer, PMMA, ceramic, or crystal substrate. Substrate **810** may be a flat substrate or a curved substrate. Substrate **810** may include a first surface **812** and a second surface **814**. Display light may be coupled into substrate **810** by an input coupler **820**, and may be reflected by first surface **812** and second surface **814** through total internal reflection, such that the display light may propagate within substrate **810**. As described above, input coupler **820** may include a grating, a refractive coupler (e.g., a wedge or a prism), or a reflective coupler (e.g., a reflective surface having a slant angle with respect to substrate **810**). For example, in one embodiment, input coupler **820** may include a prism that may couple display light of different colors into substrate **810** at a same refraction angle. In another example, input coupler **820** may include a grating coupler that may diffract light of different colors into substrate **810** at different directions. Input coupler **820** may have a coupling efficiency of greater than 10%, 20%, 30%, 50%, 75%, 90%, or higher for visible light.

[0095] Waveguide display **800** may also include a first grating **830** and a second grating **840** positioned on one or two surfaces (e.g., first surface **812** and second surface **814**) of substrate **810** for expanding incident display light beam in two dimensions in order to fill an eyebox **850** (or output or exit pupil) with the display light. First grating **830** may be configured to expand at least a portion of the display light beam along one direction, such as approximately in the x direction. Display light coupled into substrate **810** may propagate in a direction shown by a line **832**. While the display light propagates within substrate **810** along a direction shown by line **832**, a portion of the display light may be diffracted by a portion of first grating **830** towards second grating **840** as shown by a line **834** each time the display light propagating within substrate **810** reaches first grating **830**. Second grating **840** may then expand the display light from first grating **830** in a different direction (e.g., approximately in the y direction) by diffracting a portion of the display light to eyebox **850** each time the display light propagating within substrate **810** reaches second grating **840**.

[0096] FIG. **8**B illustrates an example of an eye box including two-dimensional replicated exit pupils. FIG. **8**B shows that a single input pupil **805** may be replicated by first grating **830** and second grating **840** to form an aggregated exit pupil **860** that includes a two-dimensional array of individual exit pupils **852**. For example, the exit pupil may be replicated in approximately the x direction by first grating **830** and in approximately the y direction by second grating **840**. As described above, output light from individual exit pupils **852** and propagating in a same direction may be focused onto a same location in the retina of the user's eye. Thus, a single image may be formed by the user's eye from the output light in the two-dimensional array of individual exit pupils **852**.

[0097] FIG. **9**A illustrates wave vectors of light diffracted by examples of surface-relief gratings for exit pupil expansion in a waveguide display and exit pupils for multiple colors. A circle **910** may represent wave vectors of light that may be guided by the waveguide. For light with wave vectors outside of circle **910**, the light may become evanescent. A circle **920** may represent wave vectors of light that may leak out of the waveguide because the total-internal-reflection condition is not met. Thus, the ring between circle **910** and circle **920** may represent the wave vectors of light that can be guided by the waveguide and can propagate within the waveguide through TIR. Wave vectors **932** show the light dispersion caused by the input grating, where light of different colors may have different wave vectors and different diffraction angles. Wave vectors **942** show the light dispersion caused by a front grating (e.g., first grating **830**), where light of different colors may have different diffraction angles. Wave vectors **952** show the light dispersion caused by a back grating (e.g., second grating **840**), where light of different colors may have different diffraction angles. The wave vectors for each color may form a respective closed triangle, and the triangles for different colors may share a common origin vertex **922**. Thus, the overall dispersion by the three gratings may be close to zero.

[0098] Even though the overall dispersion by the three gratings may be zero, the dispersion by each grating may cause the reduction or clipping of the field of view of the waveguide display due to the conditions under which light may be guided by the waveguide as shown by the ring between circle **910** and circle **920**. For example, for a FOV **924**, the footprints of the FOV after the diffraction by the input grating may be different for different colors due to the dispersion by the input grating. In the example shown in FIG. **9**A, a footprint **936** of the FOV for light of a first color may be located in the ring, while a portion of a footprint **934** of the FOV for light of a second color and a portion of a footprint **938** of the FOV for light of a third color may fall outside of the ring and thus may not be guided by the waveguide. In addition, the footprints of the FOV after the diffraction by the front grating may be further clipped or reduced. In the example shown in FIG. **9**A, a small portion of a footprint **946** of the FOV for the light of the first color, a large portion of a footprint **944** of the FOV for the light of the second color, and a large portion of a footprint **948** of the FOV for the light of the third color may fall outside of the ring and thus may not be guided by the waveguide and diffracted by the back grating to reach the exit pupil.

[0099] FIG. **9**B illustrates the field-of-view clipping by the examples of surface-relief gratings for exit pupil expansion in the waveguide display. For example, the FOV for the light of the first color after the diffraction by the back grating may be shown by a footprint **956**, which may be close to the full FOV. For the light of the second color, a top portion of the FOV may be clipped after diffraction by the first grating and a right portion of the FOV may be clipped after diffraction by the front grating. Thus, the FOV for the light of the second color after the diffraction by the back grating may be shown by a footprint **954**, which may be much smaller than the full FOV. Similarly, for the light of the third color, a bottom portion of the FOV may be clipped after diffraction by the first grating and a left portion of the FOV may be clipped after diffraction by the front grating. Thus, the FOV for the light of the third color after the diffraction by the back grating may be shown by a footprint **958**, which may be much smaller than the full FOV. Thus, certain color components of the image may be missing for certain fields of view. As such, in order to achieve the full FOV for different colors, two or more waveguides and the corresponding gratings may be used. In addition, as described above, the wide bandwidth of SRGs may cause crosstalk between light of different primary colors and/or from different FOVs, and thus multiple waveguides may also be used to avoid the crosstalk.

[0100] Due to the high spectral selectivity at the Bragg condition, VBGs, such as reflective VBGs, may allow for single-waveguide design without crosstalk between primary colors in a volume Bragg grating and may achieve a superior see-through quality. Thus, input coupler **530** or **640** and output coupler **540** or **650** may include a volume Bragg grating, which may be a volume hologram recorded in a holographic recording material by exposing the holographic recording material to light patterns generated by the interference between two or more coherent light beams. In volume Bragg gratings, the incident angle and the wavelength of the incident light may need to satisfy the Bragg phase-matching condition in order for the incident light to be diffracted by the Bragg grating. When a single Bragg grating is used in a waveguide-based near-eye display, the spectral and angular selectivity of the volume Bragg gratings may lead to lower efficiency because only a portion of the display light may be diffracted and reach user's eyes, and the field of view and the working wavelength range of the waveguide-based near-eye display may be limited. In some embodiments, multiplexed VBGs may be used to improve the efficiency and increase the FOV.

[0101] FIG. **10**A illustrates the front view of an example of a volume Bragg grating-based waveguide display **1000** according to certain embodiments. Waveguide display **1000** may include a substrate **1010**, which may be similar to substrate **520**. Substrate **1010** may be transparent to visible light and may include, for example, a glass, quartz, plastic, polymer, PMMA, ceramic, or crystal substrate. Substrate **1010** may be a flat substrate or a curved substrate. Substrate **1010** may include a first surface **1012** and a second surface **1014**. Display light may be coupled into substrate **1010** by an input coupler **1020**, and may be reflected by first surface **1012** and second surface **1014** through total internal reflection, such that the display light may propagate within substrate **1010**. As described above, input coupler **1020** may include a diffractive coupler (e.g., a volume holographic grating or a surface-relief grating), a refractive coupler (e.g., a wedge or a prism), or a reflective coupler (e.g., a reflective surface having a slant angle with respect to substrate **1010**). For example, in one embodiment, input coupler **1020** may include a prism that may couple display light of different colors into substrate **1010** at a same refraction angle. In another example, the input coupler may include a grating coupler that may diffract light of different colors into substrate **1010** at different directions.

[0102] Waveguide display **1000** may also include a first grating **1030** and a second grating **1040** positioned on one or two surfaces (e.g., first surface **1012** and second surface **1014**) of substrate **1010** for expanding incident display light beam in two dimensions in order to fill an eyebox **1050** with the display light. First grating **1030** may include one or more multiplexed volume Bragg gratings each configured to expand at least a portion of the display light beam (e.g., light corresponding to a certain field of view and/or a wavelength range) along one direction, as shown by lines **1032**, **1034**, and **1036**. For example, while the display light propagates within substrate **1010** along a direction shown by line **1032**, **1034**, or **1036**, a portion of the display light may be diffracted by first grating **1030** to second grating **1040** each time the display light propagating within substrate **1010** reaches first grating **1030**. Second grating **1040** may then expand the display light from first grating **1030** in a different direction by diffracting a portion of the display light to eyebox **1050** each time the display light propagating within substrate **1010** reaches second grating **1040**.

[0103] As described above, first grating **1030** and second grating **1040** may each include a multiplexed VBG that includes multiple VBGs each designed for a specific FOV range and/or wavelength range. For example, first grating **1030** may include a few hundred or more VBGs (e.g., about 300 to about 1000 VBGs) recorded by a few hundred or more exposures, where each VBG may be recorded under a different condition. Second grating **1040** may also include tens or hundreds of VBGs (e.g., 50 or more VBGs) recorded by tens or hundreds of exposures. First grating **1030** and second grating **1040** may each be a transmission grating or a reflection grating.

[0104] FIGS. **10**B and **10**C illustrate the top and side views of volume Bragg grating-based waveguide display **1000**, respectively. Input coupler **1020** may include projector optics (not shown, e.g., a lens) and a prism. Display light may be collimated and projected onto the prism by the projector optics, and may be coupled into substrate **1010** by the prism. The prism may have a refractive index that matches the refractive index of substrate **1010** and may include a wedge having a certain angle such that light coupled into substrate **1010** may be incident on surface **1012** or **1014** of substrate **1010** at an incident angle greater than the critical angle for substrate **1010**. As such, display light coupled into substrate **1010** may be guided by substrate **1010** through total internal reflection, and may be diffracted by multiple regions of first grating **1030** towards second grating **1040** as described above. Second grating **1040** may then diffract the display light out of substrate **1010** at multiple regions to replicate the exit pupil.

[0105] FIG. **11** illustrates light dispersion in an example of a volume Bragg grating-based waveguide display, such as waveguide display **1000**, according to certain embodiments. As shown in the example, a sphere **1110** may represent wave vectors of light that may be guided by the waveguide. For light with wave vectors outside of sphere **1110**, the light may become evanescent. A cone **1120** may represent wave vectors of light that may leak out of the waveguide because the total-internal-reflection condition is not met. Thus, the region of sphere **1110** outside of cone **1120** may represent the wave vectors of light that can be guided by the waveguide and can propagate within the waveguide through TIR. Point **1130** may represent the wave vector of the display light coupled into the waveguide by, for example, a prism. Wave vectors **1140** show the light dispersion caused by first grating **1030**, where light of different colors may have different diffraction angles. Wave vectors **1150** show the light dispersion caused by second grating **1040**, where light of different colors may have different diffraction angles. Thus, the light coupled out of the substrate may have some dispersion, such that the images of different colors may not perfectly overlap with each other to form one image. Therefore, the displayed image may be blurred and the resolution of the displayed image may be reduced.

[0106] FIG. **12**A illustrates an example of a volume Bragg grating **1200**. Volume Bragg grating **1200** shown in FIG. **12**A may include a transmission holographic grating that has a thickness D. The refractive index n of volume Bragg grating **1200** may be modulated at an amplitude Δn, and the grating period of volume Bragg grating **1200** may be Λ. Incident light **1210** having a wavelength λ may be incident on volume Bragg grating **1200** at an incident angle θ, and may be refracted into volume Bragg grating **1200** as incident light **1220** that propagates at an angle θ_n in volume Bragg grating **1200**. Incident light **1220** may be diffracted by volume Bragg grating **1200** into diffraction light **1230**, which may propagate at a diffraction angle &d in volume Bragg grating **1200** and may be refracted out of volume Bragg grating **1200** as diffraction light **1240**.

[0107] FIG. **12**B illustrates the Bragg condition for volume Bragg grating **1200** shown in FIG. **12**A. Volume Bragg grating **1200** may be a transmissive grating. A vector **1205** may represent the grating vector $\vec{G}$, where $|\vec{G}|=2\pi/\Lambda$. A vector **1225** may represent the incident wave vector $\vec{k}_i$, and a vector **1235** may represent the diffract wave vector $\vec{k}_d$, where $|\vec{k}_i|=|\vec{k}_d=2\pi/\lambda$. Under the Bragg phase-matching condition, $\vec{k}_i-\vec{k}_d=\vec{G}$. Thus, for a given wavelength λ, there may only be one pair of incident angle θ (or θ_n) and diffraction angle θ_d that meets the Bragg condition perfectly. Similarly, for a given incident angle θ, there may be one wavelength λ that meets the Bragg condition perfectly. As such, the diffraction may occur for a small wavelength range and in a small incident angular range around a perfect Bragg condition. The diffraction efficiency, the wavelength selectivity, and the angular selectivity of volume Bragg grating **1200** may be functions of thickness D of volume Bragg grating **1200**. For example, the full-width-half-magnitude (FWHM) wavelength range and the FWHM angular range of volume Bragg grating **1200** around the Bragg condition may be inversely proportional to thickness D of volume Bragg grating **1200**, while the maximum diffraction efficiency at the Bragg condition may be a function of $\sin^2(\alpha\times\Delta n\times D)$, where α is a coefficient. For a reflective volume Bragg grating, the maximum diffraction efficiency at the Bragg condition may be a function of $\tan h^2(\alpha\times\Delta n\times D)$.

[0108] As described above, in some designs, in order to achieve a large FOV (e.g., larger than) ±30° and diffract light of different colors, multiple polymer layers each including a Bragg grating for a different color (e.g., R, G, or B) and/or a different FOV may be arranged in a stack for coupling the display light to the user's eyes. In some designs, a multiplexed Bragg grating may be used, where each part of the multiplexed Bragg grating may be used to diffract light in a different FOV range and/or within a different wavelength range. Thus, in some designs, in order to achieve a desired diffraction efficiency and a large FOV for the full visible spectrum (e.g., from about 400 nm to about 700 nm, or from about 450 nm to about 650 nm), one or more thick volume Bragg gratings each including a large number of gratings (or holograms) recorded by a large number of exposures (e.g., holographic recordings), such as a few hundred or more than 1000, may be used.

[0109] VBGs or other holographic optical elements described above may be recorded in a holographic material (e.g., photopolymer) layer. In some embodiments, the VBGs can be recorded first and then laminated on a substrate in a near-eye display system. In some embodiments, a holographic material layer may be coated or laminated on the substrate and the VBGs may then be recorded in the holographic material layer.

[0110] In general, to record a holographic optical element in a photosensitive material layer, two coherent beams may interfere with each other at certain angles to generate a unique interference pattern in the photosensitive material layer, which may in turn generate a unique refractive index modulation pattern in the photosensitive material layer, where the refractive index modulation pattern may correspond to the light intensity pattern of the interference pattern. The photosensitive material layer may include, for example, silver halide emulsion, dichromated gelatin, photopolymers including photo-polymerizable monomers suspended in a polymer matrix, photorefractive crystals, and the like. One example of the photosensitive material layer for holographic recording is two-stage photopolymers that may include matrix precursors that can be pre-cured to form polymeric binders before holographic recording and writing monomers for holographic recording.

[0111] In one example, the photosensitive material layer may include polymeric binders, monomers (e.g., acrylic monomers), and initiating agents, such as initiators, chain transfer agents, or photosensitizing dyes. The polymeric binders may act as the support matrix. The monomers may be dispersed in the support matrix and may serve as refractive index modulators. The photosensitizing dyes may absorb light and interact with the initiators to polymerize the monomers. Thus, in each exposure (recording), the interference pattern may cause the polymerization and diffusion of the monomers to bright fringes, thus generating concentration and density gradients that may result in refractive index modulation. For example, areas with a higher concentration of monomers and polymerization may have a higher refractive index. As the exposure and polymerization proceed, fewer monomers may be available for polymerization, and the diffusion may be suppressed. After all or substantially all monomers have been polymerized, no more new gratings may be recorded in the photosensitive material layer. In a thick VBG that includes a large number of gratings recorded in a large number of exposures, display haze may be significant.

[0112] As described above, in some waveguide-based near-eye display systems, in order to expand the eyebox of the waveguide-based near-eye display, two output gratings (or two grating layers or two portions of a multiplexed grating) may generally be used to expand the display light in two dimensions or along two axes for dual-axis pupil expansion. Spatially separating the two output gratings and reducing the total number of exposures for each output grating may help to reduce the display haze because the see-through region (e.g., the middle) of the waveguide-based near-eye display may only include one output grating. For example, in some embodiments, the first output grating may be recorded with more exposures (e.g., >500 or >1000 times) and may be positioned outside of the see-through region of the waveguide-based near-eye display. The second output grating may be recorded with fewer exposures (e.g., <100 or <50 times) and may be positioned in the see-through region of the waveguide-based near-eye display. Thus, the display haze in the see-through region may be significantly reduced. However, because of the spatial separation of the two output gratings, the overall size of the waveguide-based near-eye display can be very large.

[0113] The grating couplers described above may include transmissive VBGs or reflective VBGs, which may have some similar and some different characteristics. For example, as described above, the full-width-half-magnitude (FWHM) wavelength range and the FWHM angular range of a transmissive or reflective volume Bragg grating near the Bragg condition may be inversely proportional to thickness D of the transmissive or reflective volume Bragg grating. The maximum diffraction efficiency at the Bragg condition for a transmissive VBG may be a function of $\sin^2(\alpha\times\Delta n\times D)$, where α is a coefficient and Δn is the refractive index modulation, while the maximum diffraction efficiency at the Bragg condition for a reflective VBG may be a function of $\tan h^2(\alpha\times\Delta n\times D)$. In addition, the parameters (e.g., the grating tilt angles) of the transmissive and reflective volume Bragg gratings may be different in order to couple the display light into the waveguide at certain angles such that the coupled display light can be guided by the waveguide through TIR. Because of the different grating parameters, the dispersion characteristics of transmissive gratings and reflective gratings may be different.

[0114] FIG. **13**A illustrates an example of a reflective volume Bragg grating **1300** in a waveguide display according to certain embodiments. The grating tilt angle α of reflective VBG **1300** may need to be within a certain range to reflectively diffract the display light. If the grating tilt angle α of reflective VBG **1300** is greater than a certain value, reflective VBG **1300** may become a transmissive VBG, the distance between two consecutive locations where the display light may reach the grating may be too large (and thus the exit pupil may be sparsely replicated in the eyebox), or the display light may become evanescent. In one example, the grating tilt angle α of reflective VBG **1300** may be about 30°.

[0115] FIG. **13**B illustrates an example of a reflective VBG **1310** in a waveguide display where light diffracted by the reflective VBG is not totally reflected and guided in the waveguide. The grating tilt angle α of reflective VBG **1310** shown in FIG. **13**B may be less than a certain value. As such, light coupled into the waveguide may be incident on the surface of the waveguide at an incident angle less than the critical angle, and thus may not be totally reflected and guided in the waveguide. The grating tilt angle α of reflective VBG **1310** may be less than about 30°. Thus, the grating tilt angle α of a reflective VBG may need to be within a certain range to reflectively diffract the display light into the waveguide such that the diffracted light may be guided by the waveguide through total internal reflection.

[0116] FIG. **13**C illustrates an example of a transmissive volume Bragg grating **1350** in a waveguide display according to certain embodiments. The grating tilt angle α of transmissive VBG **1350** may also need to be within a certain range. For example, if the grating tilt angle α of transmissive VBG **1350** is lower than a certain value, transmissive VBG **1350** may become a reflective VBG, the distance between two consecutive locations where the display light may reach the grating may be too large (and thus the exit pupil may be sparsely replicated in the eyebox), or the display light may become evanescent.

[0117] FIG. **13**D illustrates an example of a transmissive VBG **1360** in a waveguide display where light diffracted by the transmissive VBG is not totally reflected and guided in the waveguide. The grating tilt angle α of transmissive VBG **1360** may be greater than a certain value, such as greater than about 60°. As such, light coupled into the waveguide may be incident on the surface of the waveguide at an incident angle less than the critical angle, and thus may not be totally reflected and guided in the waveguide. Thus, the grating tilt angle α of a transmissive VBG may need to be within a certain range to transmissively diffract the display light into the waveguide such that the diffracted light may be guided by the waveguide through total internal reflection. FIGS. **13**A-**13**D show that the grating tilt angle α may be smaller for reflective gratings than for transmissive gratings.

[0118] FIG. **14**A illustrates the light dispersion by an example of a reflective volume Bragg grating **1400** in a waveguide display according to certain embodiments. Reflective VBG **1400** may be characterized by a grating vector k_g, a thickness d, and an average refractive index n. The surface normal direction of reflective VBG **1400** is N. The amount of light dispersion by reflective VBG **1400** may be determined by:

$$\Delta\theta = \frac{\lambda_0|k_g \times N|}{n \times d|k_g \cdot k_{out}|},$$

[0119] where λ_0 is the wavelength of the light that perfectly meets the Bragg condition, and k_{out} is the wave vector of the light diffracted by reflective VBG **1400**. When the grating tilt angle α of reflective VBG **1400** is about 30°, the amount of light dispersion by reflective VBG **1400** may be approximately:

$$\Delta\theta \propto \frac{\sin 30^\circ}{d \times \cos 30^\circ} = \frac{0.58}{d}.$$

Thus, to achieve an angular resolution about 2 arcminutes, the thickness d of reflective VBG **1400** may be at least about 0.5 mm.

[0120] FIG. **14**B illustrates the light dispersion by an example of a transmissive volume Bragg grating **1450** in a waveguide display according to certain embodiments. Transmissive VBG **1450** may similarly be characterized by a grating vector k_g, a thickness d, and an average refractive index n. The surface normal direction of transmissive VBG **1450** is N. The amount of light dispersion by transmissive VBG **1450** may be determined by:

$$\Delta\theta = \frac{\lambda_0 |k_g \times N|}{n \times d |k_g \cdot k_{out}|},$$

where λ_0 is the wavelength of the light that perfectly meets the Bragg condition, and k_{out} is the wave vector of the light diffracted by transmissive VBG **1450**. When the grating tilt angle α of transmissive VBG **1450** is about 60°, the amount of light dispersion by transmissive VBG **1450** may be approximately:

$$\Delta\theta \propto \frac{\sin 60^\circ}{d \times \cos 60^\circ} = \frac{1.73}{d}.$$

Thus, to achieve an angular resolution about 2 arcminutes, the thickness d of transmissive VBG **1450** may be at least about 1.5 mm, which is about three times of the thickness of a reflective VBG with the same angular resolution and may be difficult to achieve or may cause significant display haze.

[0121] In order to reduce the thickness of the VBGs and display haze and achieve the desired resolution, dispersion compensation may be desired in a VBG-based waveguide display. According to certain embodiments, one or more pairs of gratings having matching grating vectors and operating in opposite diffraction conditions (e.g., +1 order diffraction versus −1 order diffraction) may be used to compensate for the dispersion caused by each other.

[0122] FIGS. **15**A-**15**B illustrates front and side views of an example of a volume Bragg grating-based waveguide display **1500** with exit pupil expansion and dispersion reduction according to certain embodiments. Waveguide display **1500** may be similar to waveguide display **1000**, and may include an input coupler **1520** at a different location compared with input coupler **1020**. Waveguide display **1500** may include a substrate **1510**, and a first grating **1530** and a second grating **1540** on substrate **1510**. As input coupler **1020**, input coupler **1520** may include projector optics **1522** (e.g., a lens) and a prism **1524**. Display light may be coupled into substrate **1510** by input coupler **1520** and may be guided by substrate **1510**. The display light may reach a first portion **1532** of first grating **1530** and may be diffracted by first portion **1532** of first grating **1530** to change the propagation direction and reach other portions of first grating **1530**, which may each diffract the display light towards second grating **1540**. Second grating **1540** may diffract the display light out of substrate **1510** at different locations to form multiple exit pupils as described above.

[0123] First portion **1532** and each of other portions of first grating **1530** may have matching grating vectors (e.g., having a same grating vector in the x-y plane and having a same grating vector, opposite grating vectors, or both the same and opposite grating vectors in the z direction, but recorded in different exposure durations to achieve different diffraction efficiencies). Therefore, they may compensate for the dispersion of display light caused by each other to reduce the overall dispersion, due to the opposite Bragg conditions (e.g., +1 order and −1 order diffractions) for the diffractions at first portion **1532** and each of other portions of first grating **1530**. Therefore, the overall dispersion of the display light by waveguide display **1500** may be reduced in at least one direction.

[0124] FIG. **16**A is a front view of an example of a volume Bragg grating-based waveguide display **1600** with exit pupil expansion and dispersion reduction according to certain embodiments. FIG. **16**B is a side view of the example of volume Bragg grating-based waveguide display **1600** with exit pupil expansion and dispersion reduction according to certain embodiments. Waveguide display **1600** may be similar to waveguide display **1500**, but may include an input coupler that is different from input coupler **1520**. Waveguide display **1600** may include a substrate **1610** and a first grating **1630** and a second grating **1640** on substrate **1610**. The input coupler may include projector optics **1620** (e.g., a lens) and a input grating **1622**, rather than a prism. Display light may be collimated by projector optics **1620** and projected onto input grating **1622**, which may couple the display light into substrate **1610** by diffraction as described above with respect to, for example, FIGS. **5** and **6**. The display light may reach a first portion **1632** of first grating **1630** and may be diffracted by first portion **1632** of first grating **1630** to change the propagation direction and reach other portions of first grating **1630**, which may each diffract the display light towards second grating **1640**. Second grating **1640** may diffract the display light out of substrate **1610** at different locations to form multiple exit pupils as described above.

[0125] First portion **1632** and each of other portions of first grating **1630** may have matching grating vectors (e.g., having a same grating vector in the x-y plane and a same grating vector and/or opposite grating vectors in the z direction, but recorded in different exposure durations to achieve different diffraction efficiencies). Therefore, they may compensate for the dispersion of display light caused by each other to reduce the overall dispersion in one direction, due to the opposite Bragg conditions (e.g., +1 order and −1 order diffractions) for the diffractions at first portion **1632** and each of other portions of first grating **1630**. In addition, input grating **1622** and second grating **1640** may have matching grating vectors (e.g., having the same grating vector in the x-y plane and having the same or opposite grating vectors in the z direction, but recorded in different exposure durations to achieve different diffraction efficiencies), where input grating **1622** may couple the display light into substrate **1610**, while second grating **1640** may couple the display light out of the waveguide. Therefore, input grating **1622** and second grating **1640** may compensate for the dispersion of display light caused by each other to reduce the overall dispersion in at least one direction, due to the opposite diffraction directions and opposite Bragg conditions (e.g., +1 order and −1 order diffractions) for the diffractions at input grating **1622** and second grating **1640**. In this way, the dispersion by first portion **1632** and each of other portions of first grating **1630** may be canceled out, and the dispersion by input grating **1622** and second grating **1640** may also be canceled out. Therefore, the overall dispersion of the display light by waveguide display **1600** can be minimized in any direction. As such, a higher resolution of the displayed image may be achieved.

[0126] Thus, thinner reflective or transmissive VBGs may be used as the input and output couplers and may still achieve the desired resolution. Transmissive VBGs may also allow the first and second gratings to be at least partially overlapped to reduce the physical dimensions of the waveguide display as described in detail below.

[0127] FIG. **17**A illustrates the propagation of light from different fields of view in a reflective volume Bragg grating-based waveguide display **1700** according to certain embodiments. Waveguide display **1700** may include a reflective VBG **1710**. Due to the grating tilt angle and thus the grating vector of reflective VBG **1710**, light from a positive field of view (shown by a line **1722**) may have a smaller incident angle on fringes of reflective VBG **1710** and also a smaller incident angle on the top surface **1702** of waveguide display **1700**. On the other hand, light from a negative field of view (shown by a line **1724**) may have a larger incident angle on the fringes of reflective VBG **1710** and also a larger incident angle on top surface **1702** of waveguide display **1700**.

[0128] FIG. **17**B illustrates the propagation of light from different fields of view in a transmissive volume Bragg grating-based waveguide display **1750** according to certain embodiments. Waveguide display **1750** may include a transmissive VBG **1760**. Due to the grating tilt angle differences, transmissive VBG **1760** may diffract light from different fields of view in different manners compared with reflective VBG **1710**. For example, as illustrated, light from a positive field of view (shown by a line **1772**) may have a smaller incident angle on fringes of transmissive VBG **1760** but a larger incident angle on the bottom surface **1752** of waveguide display **1750**. On the other hand, light from a negative field of view (shown by a line **1774**) may have a larger incident angle on the fringes of transmissive VBG **1760** but a smaller incident angle on the bottom surface **1752** of waveguide display **1750**. The manner of diffraction of light from different fields of view by a grating may affect the form factor of the waveguide display.

[0129] FIG. **18** illustrates an example of a reflective volume Bragg grating-based waveguide display **1800** with exit pupil expansion and dispersion reduction according to certain embodiments. Waveguide display **1800** may include a top grating **1805** and a bottom grating **1815**. In the illustrated example, top grating **1805** may be a reflective VBG, and bottom grating **1815** may also be a reflective grating. On bottom grating **1815**, an exit region **1850** represents the region where display light for the full FOV at one pupil location in the eyebox (e.g., at the center the eyebox) may be coupled out of the bottom grating. As shown in FIG. **18**, the top FOV of exit region **1850** represented by a line between a top right corner **1822** and a top left corner **1824** may map to a curve **1830** on top grating **1805**, where top right corner **1822** and top left corner **1824** of exit region **1850** may map to a location **1832** and a location **1834** on top grating **1805**, respectively. The bottom FOV of exit region **1850** represented by a line between a bottom right corner **1842** and a bottom left corner **1844** may map to a curve **1810** on top grating **1805**, where bottom right corner **1842** and bottom left corner **1844** of exit region **1850** may map to a location **1812** and a location **1814** on top grating **1805**, respectively. Thus, if curve **1830** is below the line between top right corner **1822** and top left corner **1824** of exit region **1850**, there may be some FOV clipping. As such, to preserve the full FOV, curve **1830** may be above the line between top right corner **1822** and top left corner **1824** of exit region **1850**. Therefore, the size of waveguide display **1800** may be large.

[0130] FIG. **19** illustrates an example of a transmissive volume Bragg grating-based waveguide display **1900** with exit pupil expansion and form-factor reduction according to certain embodiments. Waveguide display **1900** may include a top grating **1905** and a bottom grating **1915**. In the illustrated example, top grating **1905** may be a reflective VBG, and bottom grating **1915** may be a transmission grating. On bottom grating **1915**, an exit region **1950** represents the region where display light for the full FOV at one pupil location in the eyebox (e.g., at the center the eyebox) may be coupled out of the bottom grating. As shown in FIG. **19**, the top FOV of exit region **1950** represented by a line between a top right corner **1922** and a top left corner **1924** may map to a curve **1910** on top grating **1905**, where top right corner **1922** and top left corner **1924** of exit region **1950** may map to a location **1912** and a location **1914** on top grating **1905**, respectively. The bottom FOV of exit region **1950** represented by a line between a bottom right corner **1942** and a bottom left corner **1944** may map to a curve **1930** on top grating **1905**, where bottom right corner **1942** and bottom left corner **1944** of exit region **1950** may map to a location **1932** and a location **1934** on top grating **1905**, respectively. Thus, there can be some overlap between top grating **1905** and bottom grating **1915** to reduce the overall size of waveguide display **1900**. For example, location **1932** may be lower than top right corner **1922** and can still be mapped to bottom right corner **1942**.

[0131] FIG. **20** illustrates another example of a transmissive volume Bragg grating-based waveguide display **2000** with an image projector **2030** according to certain embodiments. Waveguide display **2000** may include a top grating **2005** and a bottom grating **2015**. Top grating **2005** may include a reflective VBG, and bottom grating **2015** may include a transmissive VBG. The exit region on bottom grating **2015** supporting the desired field of view of waveguide display **2000** at one pupil location in the eyebox (e.g., in the center of the eyebox) is represented by an octagon **2020**. A shape **2010** represents the mapping of the FOV shown by octagon **2020** to the region on top grating **2005**. As described above with respect to FIG. **19**, because bottom grating **2015** is a transmission grating, top grating **2005** and bottom grating **2015** may at least partially overlap to reduce the physical size of waveguide display **2000**.

[0132] FIG. **21** illustrates an example of a volume Bragg grating-based waveguide display **2100** with exit pupil expansion, dispersion reduction, and form-factor reduction according to certain embodiments. Waveguide display **2100** may include a substrate **2110**, which may be similar to substrate **1610** but may be much smaller than substrate **1610**. Substrate **2110** may include a first surface **2112** and a second surface **2114**. Display light from a light source (e.g., LEDs) may be coupled into substrate **2110** by an input coupler **2120**, and may be reflected by first surface **2112** and second surface **2114** through total internal reflection, such that the display light may propagate within substrate **2110**. Input coupler **2120** may include a diffractive coupler (e.g., a volume holographic grating) and may couple display light of different colors into substrate **2110** at different diffraction angles.

[0133] As waveguide display **1600**, waveguide display **2100** may also include a first grating **2130** and a second grating **2140** formed on first surface **2112** and/or second surface **2114**. For example, first grating **2130** and second grating **2140** may be formed on a same surface or two different surface of substrate **2110**. Second grating **2140** may be formed in the see-through region of the waveguide display and may overlap with an eyebox **2150** when viewed in the z direction (e.g., at a distance about 18 mm from second grating **2140** in +z or −z direction). First grating **2130** and second grating **2140** may be used for dual-axis pupil expansion to expand the incident display light beam in two dimensions to fill eyebox **2150** with the display light. First grating **2130** may be a transmission grating or a reflection grating. Second grating **2140** may include a transmission grating to at least partially overlap with first grating **2130** and reduce the form factor of waveguide display **2100** as described below.

[0134] In addition, waveguide display **2100** may also include a third grating **2160** formed on first surface **2112** or second surface **2114**. In some embodiments, third grating **2160** and first grating **2130** may be on a same surface of substrate **2110**. In some embodiments, third grating **2160** and first grating **2130** may be in different regions of a same grating or a same grating material layer as shown in FIG. **16**. In some embodiments, third grating **2160** may be spatially separate from first grating **2130**. In some embodiments, third grating **2160** and first grating **2130** may be recorded in a same number of exposures and under similar recording conditions (but may be recorded for different exposure durations to achieve different diffraction efficiencies), such that each VBG in third grating **2160** may match a respective VBG in first grating **2130** (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vectors in the z direction). For example, in some embodiments, a VBG in third grating **2160** and a corresponding VBG in first grating **2130** may have the same grating period and the same grating slant angle (and thus the same grating vector), and the same thickness. In one embodiment, third grating **2160** and first grating **2130** may have a thickness about 20 μm and may each include about 40 or more VBGs recorded through about 40 or more exposures. In some embodiments, second grating **2140** may have a thickness about 20 μm or higher, and may include about 50 or more VBGs recorded through about 50 or more exposures.

[0135] Input coupler **2120** may couple the display light from the light source into substrate **2110**. The display light may reach third grating **2160** directly or may be reflected by first surface **2112** and/or second surface **2114** to third grating **2160**, where the size of the display light beam may be slightly larger than that at input coupler **2120**. Each VBG in third grating **2160** may diffract a portion of the display light within a FOV range and a wavelength range that approximately satisfies the Bragg condition of the VBG to first grating **2130**. While the display light diffracted by a VBG in third grating **2160** propagates within substrate **2110** (e.g., along a direction shown by a line **2132**) through total internal reflection, a portion of the display light may be diffracted by the corresponding VBG in first grating **2130** to second grating **2140** each time the display light propagating within substrate **2110** reaches first grating **2130**. Second grating **2140** may then expand the display light from first grating **2130** in a different direction by diffracting a portion of the display light to eyebox **2150** each time the display light propagating within substrate **2110** reaches second grating **2140**.

[0136] Because third grating **2160** and first grating **2130** may be thin (e.g., about 20 μm), they may cause some dispersion, but the dispersion may not be as high as the dispersion of a grating having a thickness of, for example, 1 μm or thinner. Therefore, the fields of view for different colors may not be significantly affected by the dispersion. In addition, as described above, each VBG in third grating **2160** matches a respective VBG in first grating **2130** (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vector in the z direction), and the two matching VBGs work under opposite Bragg conditions (e.g., +1 order diffraction versus −1 order diffraction) due to the opposite propagation directions of the display light at the two matching VBGs. For example, as shown in FIG. **21**, the VBG in third grating **2160** may change the propagation direction of the display light from a downward direction to a rightward direction, while the VBG in first grating **2130** may change the propagation direction of the display light from a rightward direction to a downward direction. Thus, the dispersion caused by first grating **2130** may be opposite to the dispersion caused by third grating **2160** to reduce or minimize the overall dispersion.

[0137] Because first grating **2130** and second grating **2140** may only have a small number (e.g., no greater than 50) of VBGs and exposures, first grating **2130** may also be placed in the see-through region to overlap with second grating **2140**, thus reducing the size of the waveguide display. The total number of VBGs and exposures in a given see-through region may be less than, for example, 100 or fewer (e.g., no more than about 40 in first grating **2130** and no more than 50 in second grating **2140**). Thus, the display haze may be reduced significantly compared with the case where 500 or more VBGs are recorded in the see-through region.

[0138] In some embodiments, because of the fewer exposures (e.g., smaller number of gratings in a multiplexed grating), the multiplexed grating may not be able to cover the full visible light spectrum and/or the full FOV, and thus some light information (in some spectral or FOV ranges) may be lost. According to certain embodiments, in order to improve the power efficiency and to cover a broader spectrum, additional gratings may be added at different spatial locations, such as different x, y, or z locations, to spatially multiplex the gratings. In this way, light in a broader bandwidth may be diffracted at a higher diffraction efficiency by the combination of the gratings to the eyebox. This may also help to increase the pupil replication density and make the light more uniform in the eyebox.

[0139] FIG. **22**A illustrates another example of a volume Bragg grating-based waveguide display **2200** with exit pupil expansion, dispersion reduction, form-factor reduction, and power efficiency improvement according to certain embodiments. As waveguide display **2100**, waveguide display **2200** may include a substrate **2210**, which may be similar to substrate **2110**. Substrate **2210** may include a first surface **2212** and a second surface **2214**. Display light from a light source (e.g., LEDs) may be coupled into substrate **2210** by an input coupler **2220**, and may be reflected by first surface **2212** and second surface **2214** through total internal reflection, such that the display light may propagate within substrate **2210**. As described above, input coupler **2220** may include a diffractive coupler, such as a VBG, which may couple display light of different colors into substrate **2210** at different diffraction angles.

[0140] As waveguide display **2100**, waveguide display **2200** may include a first grating **2230** and a second grating **2240** formed on first surface **2212** and/or second surface **2214**. Waveguide display **2200** may also include a third grating **2260** and a fourth grating **2270** formed on first surface **2212** and/or second surface **2214**. Third grating **2260** and fourth grating **2270** may each be a multiplexed VBG that includes multiple VBGs. In some embodiments, third grating **2260**, fourth grating **2270**, and first grating **2230** may be on a same surface of substrate **2210**. In some embodiments, third grating **2260**, fourth grating **2270**, and first grating **2230** may be in different regions of a same grating or a same grating material layer.

[0141] In some embodiments, first grating **2230**, third grating **2260**, and fourth grating **2270** may each include multiple VBGs. Third grating **2260** and first grating **2230** may be recorded in multiple exposures and under similar recording conditions (but may be recorded for different exposure durations to achieve different diffraction efficiencies), such that each VBG in third grating **2260** may match a respective VBG in first grating **2230** (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vectors in the z direction). For example, in some embodiments, a VBG in third grating **2260** and a corresponding VBG in first grating **2230** may have the same grating period and the same grating slant angle (and thus the same grating vector), and the same thickness. Fourth grating **2270** and first grating **2230** may also be recorded in multiple exposures and under similar recording conditions (but for different exposure durations), such that each VBG in fourth grating **2270** may match a respective VBG in first grating **2230** (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vectors in the z direction). In some embodiments, the recording conditions for recording third grating **2260** may be different from the recording conditions for recording fourth grating **2270**, such that third grating **2260** and fourth grating **2270** may have different Bragg conditions (and different grating vectors) and thus may diffract light from different FOV ranges and/or wavelength ranges to improve the overall diffraction efficiency for visible light in a large FOV range. In some embodiments, third grating **2260** and fourth grating **2270** may have similar grating vectors and thus may diffract light from the same FOV ranges and/or wavelength ranges with similar or different diffraction efficiencies to improve the overall diffraction efficiency for light in certain FOV ranges and/or wavelength ranges.

[0142] In some embodiments, M VBGs in first grating **2230** that match the M VBGs in third grating **2260** may be recorded in one area (e.g., an upper region) of first grating **2230**, while the other M VBGs in first grating **2230** that match the M VBGs in fourth grating **2270** may be recorded in a different area (e.g., a lower region) of first grating **2230**. In one example, third grating **2260** and fourth grating **2270** may each have a thickness about 20 μm and may each include about 20 VBGs recorded through about 20 exposures. In the example, first grating **2230** may have a thickness about 20 μm and may include about 40 VBGs recorded at different regions through about 40 exposures. Second grating **2240** may have a thickness about 20 μm or higher, and may include about 50 VBGs recorded through about 50 exposures.

[0143] Input coupler **2220** may couple the display light from the light source into substrate **2210**. The display light may reach third grating **2260** directly or may be reflected by first surface **2212** and/or second surface **2214** to third grating **2260**, where the size of the display light beam may be slightly larger than that at input coupler **2220**. Each VBG in third grating **2260** may diffract a portion of the display light within a FOV range and a wavelength range that approximately satisfies the Bragg condition of the VBG to an upper region of first grating **2230**. As described above, the upper region of first grating **2230** may include VBGs that match the VBGs in third grating **2260**. Therefore, while the display light diffracted by a VBG in third grating **2260** propagates within substrate **2210** (e.g., along a direction shown by a line **2232**) through total internal reflection, a portion of the display light may be diffracted by the corresponding VBG in first grating **2230** to second grating **2240** each time the display light propagating within substrate **2210** reaches first grating **2230**.

[0144] Display light that is not diffracted by third grating **2260** (e.g., due to a less than 100% diffraction efficiency or due to a small FOV range and/or wavelength range near the Bragg condition) may continue to propagate within substrate **2210**, and may reach fourth grating **2270**. Each VBG in fourth grating **2270** may diffract a portion of the display light within a FOV range and a wavelength range that approximately satisfies the Bragg condition of the VBG to a lower region of first grating **2230**. As described above, the lower region of first grating **2230** may include VBGs that match the VBGS in fourth grating **2270**. Therefore, while the display light diffracted by a VBG in fourth grating **2270** propagates within substrate **2210** (e.g., along a direction shown by a line **2234**) through total internal reflection, a portion of the display light may be diffracted by the corresponding VBG in first grating **2230** to second grating **2240** each time the display light propagating within substrate **2210** reaches first grating **2230**. Second grating **2240** may expand the display light from first grating **2230** in a different direction (e.g., in approximately the y direction) by diffracting a portion of the display light to an eyebox **2250** (e.g., at a distance about 18 mm from second grating **2240** in +z or −z direction) each time the display light propagating within substrate **2210** reaches second grating **2240**. In this way, the display light may be expanded in two dimensions to fill eyebox **2250**.

[0145] FIG. 22B illustrates examples of replicated exit pupils at an eyebox **2280** (e.g., eyebox **2250**) of volume Bragg grating-based waveguide display **2200**. The exit pupils may include a first set of exit pupils **2282** replicated by gratings **2260**, **2230**, and **2240**, and a second set of exit pupils **2284** replicated by gratings **2270**, **2230**, and **2240**. In embodiments where gratings **2260** and gratings **2270** have different grating vectors, the first set of exit pupils **2282** and the second set of exit pupils **2284** may correspond to different FOV ranges and/or different wavelength ranges. In embodiments where gratings **2260** and gratings **2270** have similar grating vectors, the first set of exit pupils **2282** and the second set of exit pupils **2284** may correspond to a same FOV range and/or wavelength range. The first set of exit pupils **2282** and the second set of exit pupils **2284** may overlap or partially overlap. Thus, the pupil replication density may be increased, and the light may be more uniform in the eyebox, due to the diffraction of display light by two spatially multiplexed sets of VBGs.

[0146] In addition, the dispersion may be reduced in the two dimensions due to the dual diffraction in each dimension by a pair of matching gratings that operate under opposite Bragg conditions as described above. Furthermore, display light in a broader bandwidth may be diffracted at a higher diffraction efficiency by the gratings to the eyebox because of the lower number of exposures (and thus a higher refractive index modulation Δn for each VBG). Thus, the power efficiency of the waveguide display may be improved. In some embodiments, first grating **2230** and second grating **2240** may at least partially overlap to reduce the form factor of waveguide display **2200** as described above.

[0147] FIG. **23** illustrates another example of a volume Bragg grating-based waveguide display **2300** with exit pupil expansion, dispersion reduction, and form-factor reduction according to certain embodiments. As waveguide display **2100**, waveguide display **2300** may include a substrate **2310**, which may be similar to substrate **2110**. Substrate **2310** may include a first surface **2312** and a second surface **2314**. Display light from a light source (e.g., LEDs) may be coupled into substrate **2310** by an input coupler **2320**, and may be reflected by first surface **2312** and second surface **2314** through total internal reflection, such that the display light may propagate within substrate **2310**. As described above, input coupler **2320** may include a diffractive coupler, such as a VBG. Waveguide display **2300** may also include a first grating **2330** and a second grating **2340** formed on first surface **2312** and/or second surface **2314**. In the example shown in FIG. **23**, first grating **2330** and second grating **2340** may be at different locations in the x direction, and may overlap in at least a portion of the see-through region of waveguide display **2300**. First grating **2330** and second grating **2340** may be used for dual-axis pupil expansion to expand the incident display light beam in two dimensions to fill an eyebox **2350** (e.g., at a distance about 18 mm from second grating **2340** in +z or −z direction) with the display light. For example, first grating **2330** may expand the display light beam in approximately the y direction, while second grating **2340** may expand the display light beam in approximately the x direction.

[0148] In addition, waveguide display **2300** may include a third grating **2360** formed on first surface **2312** and/or second surface **2314**. In some embodiments, third grating **2360** and first grating **2330** may be arranged at different locations in the y direction on a same surface of substrate **2310**. In some embodiments, third grating **2360** and first grating **2330** may be in different regions of a same grating or a same grating material layer. In some embodiments, third grating **2360** may be spatially separate from first grating **2330**. In some embodiments, third grating **2360** and first grating **2330** may be recorded in a same number of exposures and under similar recording conditions (but may be recorded for different exposure durations to achieve different diffraction efficiencies), such that each VBG in third grating **2360** may match a respective VBG in first grating **2330** (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vectors in the z direction).

[0149] Input coupler **2320** may couple the display light from the light source into substrate **2310**. The display light may propagate approximately along the x direction within substrate **2310**, and may reach third grating **2360** directly or may be reflected by first surface **2312** and/or second surface **2314** to third grating **2360**. Each VBG in third grating **2360** may diffract a portion of the display light within a FOV range and a wavelength range that approximately satisfies the Bragg condition of the VBG downward to first grating **2330**. While the display light diffracted by a VBG in third grating **2360** propagates within substrate **2310** along a direction (e.g., approximately in the y direction shown by a line **2332**) through total internal reflection, a portion of the display light may be diffracted by the corresponding VBG in first grating **2330** to second grating **2340** each time the display light propagating within substrate **2310** reaches first grating **2330**. Second grating **2340** may then expand the display light from first grating **2330** in a different direction (e.g., approximately in the x direction) by diffracting a portion of the display light to eyebox **2350** each time the display light propagating within substrate **2310** reaches second grating **2340**. Input coupler **2320** and second grating **2340** may include matching VBGs (e.g., VBGs with same grating vectors in the x-y plane and the same or opposite grating vectors in the z direction) to reduce the overall dispersion caused by input coupler **2320** and second grating **2340**. Similarly, gratings **2330** and **2360** may include matching VBGs (e.g., VBGs with same grating vectors in the x-y plane and having the same and/or opposite grating vectors in the z direction) to reduce the overall dispersion caused by gratings **2330** and **2360**. Thus, the overall dispersion by the gratings in waveguide display **2300** may be reduced or minimized.

[0150] Each of first grating **2330** and second grating **2340** may have a thickness less than, for example, 100 μm (e.g., 20 μm), and may include, for example, fewer than 50 VBGs. Thus, any area in the optical see-through region of waveguide display **2300** may include fewer than 100 VBGs. As such, the display haze may not be significant. In addition, first grating **2330** and second grating **2340** may at least partially overlap to reduce the form factor of waveguide display **2300**, and thus the physical dimensions of waveguide display **2300** may be similar to the physical dimensions of a lens in a regular pair of eye glasses.

[0151] FIG. 23B illustrates an example of a volume Bragg grating-based waveguide display **2305** with exit pupil expansion, dispersion reduction, form-factor reduction, and power efficiency improvement according to certain embodiments. As waveguide display **2300**, waveguide display **2305** may include a first grating **2335**, a second grating **2345**, a third grating **2365**, and a fourth grating **2375** formed on a first surface **2316** and/or a second surface **2318** of a substrate **2315**. First grating **2335**, a second grating **2345**, third grating **2365**, and fourth grating **2375** may each include a multiplexed VBG that includes multiple VBGs. In some embodiments, third grating **2365**, fourth grating **2375**, and first grating **2335** may be on a same surface of substrate **2315**. In some embodiments, third grating **2365**, fourth grating **2375**, and first grating **2335** may be in different regions of a same grating or a same grating material layer.

[0152] Each VBG in third grating **2365** may have a grating vector matching a grating vector of a respective VBG in first grating **2335** (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vectors in the z direction), and each VBG in fourth grating **2375** may have a grating vector matching a grating vector of a respective VBG in fourth grating **2335** (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vectors in the z direction). In some embodiments, third grating **2365** and fourth grating **2375** may have different grating vectors and thus may diffract light from different FOV ranges and/or wavelength ranges to improve the overall diffraction efficiency for visible light in a large FOV range. In some embodiments, third grating **2365** and fourth grating **2375** may have similar grating vectors and thus may diffract light from the same FOV ranges and/or wavelength ranges with similar or different diffraction efficiencies to improve the overall diffraction efficiency for light in certain FOV ranges and/or wavelength ranges.

[0153] Input coupler **2325** may couple the display light from the light source into substrate **2315**. The display light may reach third grating **2365** directly or may be reflected by first surface **2316** and/or second surface **2318** to third grating **2365**. Each VBG in third grating **2365** may diffract a portion of the display light within a FOV range and a wavelength range that approximately satisfies the Bragg condition of the VBG to a left region of first grating **2335**. While the display light diffracted by a VBG in third grating **2365** propagates within substrate **2315** (e.g., along a direction shown by a line **2336**) through total internal reflection, a portion of the display light may be diffracted by the corresponding VBG in first grating **2335** to second grating **2345** each time the display light propagating within substrate **2315** reaches first grating **2335**.

[0154] Display light that is not diffracted by third grating **2365** (e.g., due to a less than 100% diffraction efficiency or due to a small FOV range and/or wavelength range near the Bragg condition) may continue to propagate within substrate **2315**, and may reach fourth grating **2375**. Each VBG in fourth grating **2375** may diffract a portion of the display light within a FOV range and a wavelength range that approximately satisfies the Bragg condition of the VBG to a right region of first grating **2335**. While the display light diffracted by a VBG in fourth grating **2375** propagates within substrate **2315** (e.g., along a direction shown by a line **2338**) through total internal reflection, a portion of the display light may be diffracted by the corresponding VBG in first grating **2335** to second grating **2345** each time the display light propagating within substrate **2315** reaches first grating **2335**.

[0155] Second grating **2345** may expand the display light from first grating **2335** in a different direction (e.g., in approximately the y direction) by diffracting a portion of the display light to an eyebox **2355** (e.g., at a distance about 18 mm from second grating **2345** in +z or −z direction) each time the display light propagating within substrate **2315** reaches second grating **2345**. In this way, the display light may be expanded in two dimensions to fill eyebox **2355**. The resultant exit pupils may include a first set of exit pupils replicated by gratings **2365**, **2335**, and **2345**, and a second set of exit pupils replicated by gratings **2375**, **2335**, and **2345**. In embodiments where gratings **2365** and gratings **2375** have different grating vectors, the first set of exit pupils and the second set of exit pupils may correspond to different FOV ranges and/or different wavelength ranges. In embodiments where gratings **2365** and gratings **2375** have similar grating vectors, the first set of exit pupils and the second set of exit pupils may correspond to a same FOV range and/or wavelength range. The first set of exit pupils and the second set of exit pupils may overlap or partially overlap. Thus, the pupil replication density may be increased, and the light may be more uniform in the eyebox, due to the diffraction of display light by two spatially multiplexed sets of VBGs.

[0156] FIG. **24**A is a front view of an example of a volume Bragg grating-based waveguide display **2400** including an image projector **2420** and multiple polymer layers according to certain embodiments. FIG. **24**B is a side view of the example of volume Bragg grating-based waveguide display **2400** including image projector **2420** according to certain embodiments. Waveguide display **2400** may be similar to waveguide display **1600**, but may include multiple polymer layers on one or more waveguide plates, where the input grating (e.g., input grating **1622**), top grating (e.g., first grating **1630**), and bottom grating (e.g., second grating **1640**) may each be split into multiple gratings recorded in the multiple polymer layers, where the gratings on each polymer layer may cover different respective FOVs and light spectra, and the combination of the multiple polymer layers may provide the full FOV and spectral coverage. In this way, each polymer layer can be thin (e.g., about 20 μm to about 100 μm) and can be exposed for fewer times (e.g., less than about 100) to record fewer gratings to reduce haziness, and the overall efficiency of the multiple polymer layers can still be high for the full FOV and spectrum.

[0157] In the example shown in FIGS. **24**A and **24**B, waveguide display **2400** may include a first polymer layer **2412** and a second polymer layer **2414** on one or more plates or substrates. Each polymer layer **2412** or **2414** may include part of an input grating **2422**, a top grating **2430**, and a bottom grating **2440**. Display light may be collimated and projected onto input grating **2422** by image projector **2420**. Input grating **2422** may couple the display light into a waveguide **2410** by diffraction as described above with respect to, for example, FIGS. **5** and **6**. The display light may reach a first portion **2432** of top grating **2430** and may be diffracted by the first portion **2432** of top grating **2430** to change the propagation direction and reach other portions of top grating **2430**, which may each diffract the display light towards bottom grating **2440**. Bottom grating **2440** may then diffract the display light out of waveguide **2410** at different locations to form multiple exit pupils as described above.

[0158] First portion **2432** and each of other portions of top grating **2430** may have matching grating vectors (e.g., having the same grating vector in the x-y plane and having the same and/or opposite grating vectors in the z direction, but recorded in different exposure durations to achieve different diffraction efficiencies). Therefore, they may compensate for the dispersion of display light caused by each other to reduce the overall dispersion, due to the opposite Bragg conditions (e.g., +1 order and −1 order diffractions) for the diffractions at first portion **2432** and each of other portions of top grating **2430**. In addition, input grating **2422** and bottom grating **2440** may have matching grating vectors (e.g., having the same grating vector in the x-y plane and having the same or opposite grating vectors in the z direction, but recorded in different exposure durations to achieve different diffraction efficiencies), where input grating **2422** may couple the display light into waveguide **2410**, while bottom grating **2440** may couple the display light out of waveguide **2410**. Therefore, input grating **2422** and bottom grating **2440** may compensate for the dispersion of display light caused by each other to reduce the overall dispersion, due to the opposite diffraction directions and opposite Bragg conditions (e.g., +1 order and −1 order diffractions) for the diffractions at input grating **2422** and bottom grating **2440**.

In this way, the dispersion by first portion **2432** and each of other portions of top grating **2430** may be canceled out, and the dispersion by input grating **2422** and bottom grating **2440** may also be canceled out. Therefore, the overall dispersion of the display light by waveguide display **2400** can be minimized in any direction. As such, a higher resolution of the displayed image may be achieved even if the polymer layers **2412** and **2414** are thin and transmissive VBGs are recorded in the thin polymer layers.

[0159] FIG. **25** illustrates an example of a volume Bragg grating-based waveguide display **2500** including multiple grating layers for different fields of view and/or light wavelengths according to certain embodiments. In waveguide display **2500**, gratings may be spatially multiplexed along the z direction. For example, waveguide display **2500** may include multiple substrates, such as substrates **2510**, **2512**, **2514**, and the like. The substrates may include a same material or materials having similar refractive indexes. One or more VBGs (e.g., VBGs **2520**, **2522**, **2524**, etc.) may be made on each substrate, such as recorded in a holographic material layer formed on the substrate. The VBGs may be reflection gratings or transmission gratings. The substrates with the VBGs may be arranged in a substrate stack along the z direction for spatial multiplexing. Each VBG may be a multiplexed VBG that includes multiple gratings designed for different Bragg conditions to couple display light in different wavelength ranges and/or different FOVs into or out of the waveguide.

[0160] In the example shown in FIG. **25**, VBG **2520** may couple light **2534** from the positive field of view into the waveguide as shown by light **2544** within the waveguide. VBG **2522** may couple light **2530** from around 0° field of view into the waveguide as shown by light **2540** within the waveguide. VBG **2524** may couple light **2532** from the negative field of view into the waveguide as shown by light **2542** within the waveguide. As described above, each of VBGs **2520**, **2522**, and **2524** may be a multiplexed VBG with many exposures, and thus may couple light from different FOV ranges into or out of the waveguide.

[0161] In some embodiments, because the diffraction efficiency of a transmission grating may be polarization sensitive and the incoming display light may be unpolarized, some components of the display light may not be diffracted by the grating and thus the efficiency of the waveguide display may be reduced. To improve the efficiency for unpolarized light or light in a certain polarization state, a polarization convertor and two spatially multiplexed gratings may be used to couple the display light into or out of the waveguide.

[0162] FIG. **26** illustrates an example of a waveguide display **2600** including two multiplexed volume Bragg gratings **2610** and **2640** and a polarization convertor **2630** between the two multiplexed volume Bragg gratings **2610** and **2640** according to certain embodiments. A first VBG **2610** may be formed on a substrate **2620** or on a surface of polarization convertor **2630**. A second VBG **2640** may be formed on a substrate **2650** or on another surface of polarization convertor **2630**.

[0163] Unpolarized light **2602** may include s-polarized light and p-polarized light. First VBG **2610** may diffract a majority of the s-polarized light and a portion of the p-polarized light as shown by diffracted light **2604**. Diffracted light **2604** may be partially converted by polarization convertor **2630** and pass through second VBG **2640** without being diffracted by second VBG **2640** as shown by transmitted light **2606** because the Bragg condition is not satisfied. The portion **2608** of the p-polarized light that is not diffracted by first VBG **2610** may pass through polarization convertor **2630** and may be converted into s-polarized light and may be diffracted by second VBG **2640**, where the diffracted light **2612** may have the same propagation direction as transmitted light **2606**. In this way, unpolarized light **2602** may be more efficiently diffracted by waveguide display **2600**.

[0164] External light (e.g., from an external light source, such as a lamp or the sun) may be reflected at a surface of a grating coupler and back to the grating coupler, where the reflected light may be diffracted by the grating coupler to generate rainbow images. In some waveguide display, ambient light with a large incident angle outside of the see-through field of view of the waveguide display may also be diffracted by the grating couplers to generate rainbow images. According to some embodiments, additional structures, such as a reflective coating layer (e.g., for light from a large see-through FOV) and/or an antireflective coating layer (e.g., for light from a small see-through FOV), may be used in the waveguide display to reduce optical artifacts, such as rainbow effects. For example, an angular-selective transmissive layer may be placed in front of (or behind) the waveguide and the grating coupler of a waveguide display to reduce the artifacts caused by external light source. The angular-selective transmissive layer may be configured to reflect, diffract, or absorb ambient light with an incident angle greater than one half of the see-through field of view of the waveguide display, while allowing ambient light within the see-through field of view of the near-eye display to pass through and reach user's eyes with little or no loss. The angular-selective transmissive layer may include, for example, coating that may include one or more dielectric layers, diffractive elements such as gratings (e.g., meta-gratings), nanostructures (e.g., nanowires, nano-pillars, nano-prisms, nano-pyramids), and the like.

[0165] FIG. **27** illustrates an example of a waveguide display **2700** including an anti-reflection layer **2750** and an angular-selective transmissive layer **2740** according to certain embodiments. Waveguide display **2700** may include a waveguide **2710** and a grating coupler **2720** at the bottom surface of waveguide **2710**. Grating coupler **2720** may be similar to the grating couplers described above. External light **2730** incident on waveguide **2710** may be refracted into waveguide **2710** as external light **2732** and may then be diffracted by grating coupler **2720**. The diffracted light may include a 0^{th} order diffraction **2734** (e.g., refractive diffraction) and a −1st order diffraction (not shown). The height, period, and/or slant angle of grating coupler **2720** may be configured such that the −1st order diffraction may be reduced or minimized for the external light.

[0166] Waveguide display **2700** may include anti-reflection layer **2750** on bottom surface **2722** of grating coupler **2720**. Anti-reflection layer **2750** may include, for example, one or more dielectric thin film layers or other anti-reflection layers coated on bottom surface **2722**, and may be used to reduce the reflection of the external light at bottom surface **2722**. Thus, little or no external light may be reflected at bottom surface **2722** of grating coupler **2720** back to grating coupler **2720**, and therefore the rainbow ghost that might otherwise be formed due to the diffraction of external light reflected at bottom surface **2722** by grating coupler **2720**

may be reduced or minimized. Some portions of the display light may be diffracted by grating coupler **2720** and may be coupled out of waveguide **2710** towards user's eyes (e.g., due to -1^{st} order diffraction). Anti-reflection layer **2750** may also help to reduce the reflection of the portions of the display light that are coupled out of waveguide **2710** by grating coupler **2720**.

[0167] Angular-selective transmissive layer **2740** may be coated on the top surface of waveguide **2710** or grating coupler **2720**. Angular-selective transmissive layer **2740** may have a high reflectivity, high diffraction efficiency, or high absorption for incident light with an incident angle greater than a certain threshold value, and may have a low loss for incident light with an incident angle lower than the threshold value. The threshold value may be determined based on the see-through field of view of waveguide display **2700**. For example, incident light **2760** with an incident angle greater than the see-through field of view may be mostly reflected, diffracted, or absorbed by angular-selective transmissive layer **2740**, and thus may not reach waveguide **2710**. External light **2730** with an incident angle within the see-through field of view may mostly pass through angular-selective transmissive layer and waveguide **2710**, and may be refracted or diffracted by grating coupler **2720**.

[0168] The angular-selective transmissive layer **2740** described above may be implemented in various ways. In some embodiments, the angular-selective transmissive layer may include one or more dielectric layers (or air gap). Each dielectric layer may have a respective refractive index, and adjacent dielectric layers may have different refractive indexes. In some embodiments, the angular-selective transmissive layer may include, for example, micro mirrors or prisms, grating, meta-gratings, nanowires, nano-pillars, or other micro- or nano-structures. In some examples, the angular-selective transmissive layer may include gratings (e.g., surface-relief gratings or holographic gratings) with small grating periods formed on a substrate. The gratings may only diffract light with large incidence angles (e.g., about 75° to about 90°) and the diffracted light may propagate in directions such that the diffracted light may not reach the eyebox. The grating period may be, for example, less than 300 nm (e.g., about 200 nm) such that the angular-selective transmissive layer may not affect light within the see-through field of view. In some examples, the angular-selective transmissive layer may include micro-scale or nano-scale anisotropic structures that may reflect, diffract, or absorb incident light with large incident angles. The anisotropic structures may include, for example, large-aspect-ratio nanoparticles aligned and immersed in transparent media, nanowire arrays, certain liquid crystal materials, and the like.

[0169] Embodiments of the invention may be used to implement components of an artificial reality system or may be implemented in conjunction with an artificial reality system. Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, for example, a virtual reality (VR), an augmented reality (AR), a mixed reality (MR), a hybrid reality, or some combination and/or derivatives thereof. Artificial reality content may include completely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, haptic feedback, or some combination thereof, and any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional effect to the viewer). Additionally, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in an artificial reality and/or are otherwise used in (e.g., perform activities in) an artificial reality. The artificial reality system that provides the artificial reality content may be implemented on various platforms, including a head-mounted display (HMD) connected to a host computer system, a standalone HMD, a mobile device or computing system, or any other hardware platform capable of providing artificial reality content to one or more viewers.

[0170] FIG. **28** is a simplified block diagram of an example electronic system **2800** of an example near-eye display (e.g., HMD device) for implementing some of the examples disclosed herein. Electronic system **2800** may be used as the electronic system of an HMD device or other near-eye displays described above. In this example, electronic system **2800** may include one or more processor(s) **2810** and a memory **2820**. Processor(s) **2810** may be configured to execute instructions for performing operations at a number of components, and can be, for example, a general-purpose processor or microprocessor suitable for implementation within a portable electronic device. Processor(s) **2810** may be communicatively coupled with a plurality of components within electronic system **2800**. To realize this communicative coupling, processor(s) **2810** may communicate with the other illustrated components across a bus **2840**. Bus **2840** may be any subsystem adapted to transfer data within electronic system **2800**. Bus **2840** may include a plurality of computer buses and additional circuitry to transfer data.

[0171] Memory **2820** may be coupled to processor(s) **2810**. In some embodiments, memory **2820** may offer both short-term and long-term storage and may be divided into several units. Memory **2820** may be volatile, such as static random access memory (SRAM) and/or dynamic random access memory (DRAM) and/or non-volatile, such as read-only memory (ROM), flash memory, and the like. Furthermore, memory **2820** may include removable storage devices, such as secure digital (SD) cards. Memory **2820** may provide storage of computer-readable instructions, data structures, program modules, and other data for electronic system **2800**. In some embodiments, memory **2820** may be distributed into different hardware modules. A set of instructions and/or code might be stored on memory **2820**. The instructions might take the form of executable code that may be executable by electronic system **2800**, and/or might take the form of source and/or installable code, which, upon compilation and/or installation on electronic system **2800** (e.g., using any of a variety of generally available compilers, installation programs, compression/decompression utilities, etc.), may take the form of executable code.

[0172] In some embodiments, memory **2820** may store a plurality of application modules **2822** through **2824**, which may include any number of applications. Examples of applications may include gaming applications, conferencing applications, video playback applications, or other suitable applications. The applications may include a depth sensing function or eye tracking function. Application modules **2822-4924** may include particular instructions to be executed by processor(s) **2810**. In some embodiments, certain applications or parts of application modules **2822-4924**

may be executable by other hardware modules **2880**. In certain embodiments, memory **2820** may additionally include secure memory, which may include additional security controls to prevent copying or other unauthorized access to secure information.

[0173] In some embodiments, memory **2820** may include an operating system **2825** loaded therein. Operating system **2825** may be operable to initiate the execution of the instructions provided by application modules **2822-4924** and/or manage other hardware modules **2880** as well as interfaces with a wireless communication subsystem **2830** which may include one or more wireless transceivers. Operating system **2825** may be adapted to perform other operations across the components of electronic system **2800** including threading, resource management, data storage control and other similar functionality.

[0174] Wireless communication subsystem **2830** may include, for example, an infrared communication device, a wireless communication device and/or chipset (such as a Bluetooth® device, an IEEE 802.11 device, a Wi-Fi device, a WiMax device, cellular communication facilities, etc.), and/or similar communication interfaces. Electronic system **2800** may include one or more antennas **2834** for wireless communication as part of wireless communication subsystem **2830** or as a separate component coupled to any portion of the system. Depending on desired functionality, wireless communication subsystem **2830** may include separate transceivers to communicate with base transceiver stations and other wireless devices and access points, which may include communicating with different data networks and/or network types, such as wireless wide-area networks (WWANs), wireless local area networks (WLANs), or wireless personal area networks (WPANs). A WWAN may be, for example, a WiMax (IEEE 802.16) network. A WLAN may be, for example, an IEEE 802.11x network. A WPAN may be, for example, a Bluetooth network, an IEEE 802.15x, or some other types of network. The techniques described herein may also be used for any combination of WWAN, WLAN, and/or WPAN. Wireless communications subsystem **2830** may permit data to be exchanged with a network, other computer systems, and/or any other devices described herein. Wireless communication subsystem **2830** may include a means for transmitting or receiving data, such as identifiers of HMD devices, position data, a geographic map, a heat map, photos, or videos, using antenna(s) **2834** and wireless link(s) **2832**. Wireless communication subsystem **2830**, processor (s) **2810**, and memory **2820** may together comprise at least a part of one or more of a means for performing some functions disclosed herein.

[0175] Embodiments of electronic system **2800** may also include one or more sensors **2890**. Sensor(s) **2890** may include, for example, an image sensor, an accelerometer, a pressure sensor, a temperature sensor, a proximity sensor, a magnetometer, a gyroscope, an inertial sensor (e.g., a module that combines an accelerometer and a gyroscope), an ambient light sensor, or any other similar module operable to provide sensory output and/or receive sensory input, such as a depth sensor or a position sensor. For example, in some implementations, sensor(s) **2890** may include one or more inertial measurement units (IMUs) and/or one or more position sensors. An IMU may generate calibration data indicating an estimated position of the HMD device relative to an initial position of the HMD device, based on measurement signals received from one or more of the position sensors. A position sensor may generate one or more measurement signals in response to motion of the HMD device. Examples of the position sensors may include, but are not limited to, one or more accelerometers, one or more gyroscopes, one or more magnetometers, another suitable type of sensor that detects motion, a type of sensor used for error correction of the IMU, or some combination thereof. The position sensors may be located external to the IMU, internal to the IMU, or some combination thereof. At least some sensors may use a structured light pattern for sensing.

[0176] Electronic system **2800** may include a display module **2860**. Display module **2860** may be a near-eye display, and may graphically present information, such as images, videos, and various instructions, from electronic system **2800** to a user. Such information may be derived from one or more application modules **2822-4924**, virtual reality engine **2826**, one or more other hardware modules **2880**, a combination thereof, or any other suitable means for resolving graphical content for the user (e.g., by operating system **2825**). Display module **2860** may use liquid crystal display (LCD) technology, light-emitting diode (LED) technology (including, for example, OLED, ILED, μLED, AMOLED, TOLED, etc.), light emitting polymer display (LPD) technology, or some other display technology.

[0177] Electronic system **2800** may include a user input/output module **2870**. User input/output module **2870** may allow a user to send action requests to electronic system **2800**. An action request may be a request to perform a particular action. For example, an action request may be to start or end an application or to perform a particular action within the application. User input/output module **2870** may include one or more input devices. Example input devices may include a touchscreen, a touch pad, microphone(s), button(s), dial(s), switch(es), a keyboard, a mouse, a game controller, or any other suitable device for receiving action requests and communicating the received action requests to electronic system **2800**. In some embodiments, user input/output module **2870** may provide haptic feedback to the user in accordance with instructions received from electronic system **2800**. For example, the haptic feedback may be provided when an action request is received or has been performed.

[0178] Electronic system **2800** may include a camera **2850** that may be used to take photos or videos of a user, for example, for tracking the user's eye position. Camera **2850** may also be used to take photos or videos of the environment, for example, for VR, AR, or MR applications. Camera **2850** may include, for example, a complementary metal-oxide-semiconductor (CMOS) image sensor with a few millions or tens of millions of pixels. In some implementations, camera **2850** may include two or more cameras that may be used to capture 3-D images.

[0179] In some embodiments, electronic system **2800** may include a plurality of other hardware modules **2880**. Each of other hardware modules **2880** may be a physical module within electronic system **2800**. While each of other hardware modules **2880** may be permanently configured as a structure, some of other hardware modules **2880** may be temporarily configured to perform specific functions or temporarily activated. Examples of other hardware modules **2880** may include, for example, an audio output and/or input module (e.g., a microphone or speaker), a near field communication (NFC) module, a rechargeable battery, a battery management system, a wired/wireless battery charging system, etc.

In some embodiments, one or more functions of other hardware modules **2880** may be implemented in software.

[0180] In some embodiments, memory **2820** of electronic system **2800** may also store a virtual reality engine **2826**. Virtual reality engine **2826** may execute applications within electronic system **2800** and receive position information, acceleration information, velocity information, predicted future positions, or some combination thereof of the HMD device from the various sensors. In some embodiments, the information received by virtual reality engine **2826** may be used for producing a signal (e.g., display instructions) to display module **2860**. For example, if the received information indicates that the user has looked to the left, virtual reality engine **2826** may generate content for the HMD device that mirrors the user's movement in a virtual environment. Additionally, virtual reality engine **2826** may perform an action within an application in response to an action request received from user input/output module **2870** and provide feedback to the user. The provided feedback may be visual, audible, or haptic feedback. In some implementations, processor(s) **2810** may include one or more GPUs that may execute virtual reality engine **2826**.

[0181] In various implementations, the above-described hardware and modules may be implemented on a single device or on multiple devices that can communicate with one another using wired or wireless connections. For example, in some implementations, some components or modules, such as GPUs, virtual reality engine **2826**, and applications (e.g., tracking application), may be implemented on a console separate from the head-mounted display device. In some implementations, one console may be connected to or support more than one HMD.

[0182] In alternative configurations, different and/or additional components may be included in electronic system **2800**. Similarly, functionality of one or more of the components can be distributed among the components in a manner different from the manner described above. For example, in some embodiments, electronic system **2800** may be modified to include other system environments, such as an AR system environment and/or an MR environment.

[0183] The methods, systems, and devices discussed above are examples. Various embodiments may omit, substitute, or add various procedures or components as appropriate. For instance, in alternative configurations, the methods described may be performed in an order different from that described, and/or various stages may be added, omitted, and/or combined. Also, features described with respect to certain embodiments may be combined in various other embodiments. Different aspects and elements of the embodiments may be combined in a similar manner. Also, technology evolves and, thus, many of the elements are examples that do not limit the scope of the disclosure to those specific examples.

[0184] Specific details are given in the description to provide a thorough understanding of the embodiments. However, embodiments may be practiced without these specific details. For example, well-known circuits, processes, systems, structures, and techniques have been shown without unnecessary detail in order to avoid obscuring the embodiments. This description provides example embodiments only, and is not intended to limit the scope, applicability, or configuration of the invention. Rather, the preceding description of the embodiments will provide those skilled in the art with an enabling description for implementing various embodiments. Various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the present disclosure.

[0185] Also, some embodiments were described as processes depicted as flow diagrams or block diagrams. Although each may describe the operations as a sequential process, many of the operations may be performed in parallel or concurrently. In addition, the order of the operations may be rearranged. A process may have additional steps not included in the figure. Furthermore, embodiments of the methods may be implemented by hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware, or microcode, the program code or code segments to perform the associated tasks may be stored in a computer-readable medium such as a storage medium. Processors may perform the associated tasks.

[0186] It will be apparent to those skilled in the art that substantial variations may be made in accordance with specific requirements. For example, customized or special-purpose hardware might also be used, and/or particular elements might be implemented in hardware, software (including portable software, such as applets, etc.), or both. Further, connection to other computing devices such as network input/output devices may be employed.

[0187] With reference to the appended figures, components that can include memory can include non-transitory machine-readable media. The term "machine-readable medium" and "computer-readable medium" may refer to any storage medium that participates in providing data that causes a machine to operate in a specific fashion. In embodiments provided hereinabove, various machine-readable media might be involved in providing instructions/code to processing units and/or other device(s) for execution. Additionally or alternatively, the machine-readable media might be used to store and/or carry such instructions/code. In many implementations, a computer-readable medium is a physical and/or tangible storage medium. Such a medium may take many forms, including, but not limited to, non-volatile media, volatile media, and transmission media. Common forms of computer-readable media include, for example, magnetic and/or optical media such as compact disk (CD) or digital versatile disk (DVD), punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a programmable read-only memory (PROM), an erasable programmable read-only memory (EPROM), a FLASH-EPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read instructions and/or code. A computer program product may include code and/or machine-executable instructions that may represent a procedure, a function, a subprogram, a program, a routine, an application (App), a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements.

[0188] Those of skill in the art will appreciate that information and signals used to communicate the messages described herein may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0189] Terms, "and" and "or" as used herein, may include a variety of meanings that are also expected to depend at least in part upon the context in which such terms are used. Typically, "or" if used to associate a list, such as A, B, or C, is intended to mean A, B, and C, here used in the inclusive sense, as well as A, B, or C, here used in the exclusive sense. In addition, the term "one or more" as used herein may be used to describe any feature, structure, or characteristic in the singular or may be used to describe some combination of features, structures, or characteristics. However, it should be noted that this is merely an illustrative example and claimed subject matter is not limited to this example. Furthermore, the term "at least one of" if used to associate a list, such as A, B, or C, can be interpreted to mean any combination of A, B, and/or C, such as A, AB, AC, BC, AA, ABC, AAB, AABBCCC, etc.

[0190] Further, while certain embodiments have been described using a particular combination of hardware and software, it should be recognized that other combinations of hardware and software are also possible. Certain embodiments may be implemented only in hardware, or only in software, or using combinations thereof. In one example, software may be implemented with a computer program product containing computer program code or instructions executable by one or more processors for performing any or all of the steps, operations, or processes described in this disclosure, where the computer program may be stored on a non-transitory computer readable medium. The various processes described herein can be implemented on the same processor or different processors in any combination.

[0191] Where devices, systems, components or modules are described as being configured to perform certain operations or functions, such configuration can be accomplished, for example, by designing electronic circuits to perform the operation, by programming programmable electronic circuits (such as microprocessors) to perform the operation such as by executing computer instructions or code, or processors or cores programmed to execute code or instructions stored on a non-transitory memory medium, or any combination thereof. Processes can communicate using a variety of techniques, including, but not limited to, conventional techniques for inter-process communications, and different pairs of processes may use different techniques, or the same pair of processes may use different techniques at different times.

[0192] The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. It will, however, be evident that additions, subtractions, deletions, and other modifications and changes may be made thereunto without departing from the broader spirit and scope as set forth in the claims. Thus, although specific embodiments have been described, these are not intended to be limiting. Various modifications and equivalents are within the scope of the following claims.

What is claimed is:

1. A waveguide display comprising:

a substrate transparent to visible light; and

a first volume Bragg grating (VBG), a second VBG, and a third VBG coupled to the substrate,

wherein the first VBG is configured to couple display light into the substrate as guided wave towards a first region of the second VBG;

wherein the second VBG is configured to:

diffract, at the first region of the second VBG, the display light from the first VBG to a first direction; and

diffract, at two or more regions of the second VBG along the first direction, the display light from the first region to a second direction towards the third VBG; and

wherein the third VBG is configured to couple the display light from each of the two or more regions of the second VBG out of the substrate at two or more regions of the third VBG along the second direction.

2. The waveguide display of claim **1**, wherein the first VBG and the third VBG have a same grating vector in a plane perpendicular to a surface normal direction of the substrate.

3. The waveguide display of claim **1**, wherein the first VBG, the second VBG, and the third VBG are configured to diffract the display light from a same field of view range and in a same wavelength range.

4. The waveguide display of claim **1**, wherein each of the first VBG, the second VBG, and the third VBG includes a reflective VBG or a transmissive VBG.

5. The waveguide display of claim **1**, wherein:

the third VBG includes a transmissive VBG; and

the second VBG overlaps with the third VBG in a see-through region of the waveguide display.

6. The waveguide display of claim **1**, wherein at least one of the first VBG, the second VBG, or the third VBG includes a multiplexed VBG.

7. The waveguide display of claim **6**, wherein:

the first VBG includes a first set of VBGs;

the third VBG includes a second set of VBGs; and

each VBG in the first set of VBGs and a corresponding VBG in the second set of VBGs have a same grating vector in a plane perpendicular to a surface normal direction of the substrate and are configured to diffract the display light from a same field of view range and in a same wavelength range.

8. The waveguide display of claim **6**, wherein at least one of the first VBG, the second VBG, or the third VBG includes VBGs in two or more holographic material layers.

9. The waveguide display of claim **8**, further comprising a polarization convertor between two holographic material layers of the two or more holographic material layers.

10. The waveguide display of claim **1**, further comprising an anti-reflection layer configured to reduce reflection of ambient light into the substrate.

11. The waveguide display of claim **1**, further comprising an angular-selective transmissive layer configured to reflect, diffract, or absorb ambient light incident on the angular-selective transmissive layer with an incidence angle greater than a threshold value.

12. The waveguide display of claim **1**, wherein:

each of the second VBG and the third VBG is characterized by a respective thickness less than 100 μm; and

the waveguide display is characterized by an angular resolution less than 2 arcminutes.

13. The waveguide display of claim **1**, wherein the first region of the second VBG and a second region of the two or more regions of the second VBG have a same grating vector in a plane perpendicular to a surface normal direction of the substrate.

14. The waveguide display of claim **1**, further comprising:

a light source configured to generate the display light; and

projector optics configure to collimate the display light and direct the display light to the first VBG.

15. A waveguide display comprising:

a substrate transparent to visible light;

a coupler configured to couple display light into the substrate as guided wave in the substrate; and

a first volume Bragg grating (VBG) and a second VBG coupled to the substrate,

wherein the first VBG is configured to:

diffract, at a first region of the first VBG, the display light in the substrate to a first direction; and

diffract, at two or more regions of the first VBG along the first direction, the display light from the first region to a second direction towards the second VBG; and

wherein the second VBG is configured to couple the display light from each of the two or more regions of the first VBG out of the substrate at two or more regions of the second VBG along the second direction.

16. The waveguide display of claim **15**, wherein:

the first VBG is characterized by a thickness less than 100 μm; and

the waveguide display is characterized by an angular resolution less than 2 arcminutes.

17. The waveguide display of claim **15**, wherein:

the second VBG includes a transmissive VBG; and

the first VBG overlaps with the second VBG in a see-through region of the waveguide display.

18. The waveguide display of claim **15**, wherein at least one of the first VBG or the second VBG includes VBGs in two or more holographic material layers.

19. The waveguide display of claim **15**, wherein the coupler includes a diffractive coupler, a refractive coupler, or a reflective coupler.

20. The waveguide display of claim **15**, wherein at least one of the first VBG or the second VBG includes a multiplexed VBG.

21. The waveguide display of claim **15**, wherein each of the first VBG and the second VBG includes a transmissive VBG or a reflective VBG.

22. The waveguide display of claim **15**, wherein the first region of the first VBG and a second region of the two or more regions of the first VBG have a same grating vector in a plane perpendicular to a surface normal direction of the substrate.

* * * * *