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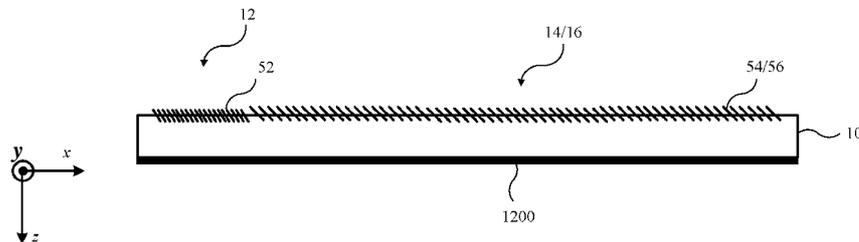(54) **Title:** WAVEGUIDE-BASED DISPLAY SYSTEM



Fig. 12

(57) **Abstract:** A display system comprises an optical waveguide and a light engine. The light engine generates multiple input beams
which form a virtual image. An incoupling grating of the waveguide couples each beam into an intermediate grating of the wave -
guide, in which that beam is guided onto multiple splitting regions. The intermediate grating, formed by modulations on a first sur-
face of the waveguide, splits that beam at the splitting regions to provide multiple substantially parallel versions of that beam. Those
multiple versions are coupled into an exit grating of the waveguide, in which the multiple versions are guided onto multiple exit re -
gions. The exit grating diffracts the multiple versions of that beam outwardly. The multiple input beams thus cause multiple exit
beams to exit the waveguide which form a version of the virtual image. A polarization state of each beam interacting with the modu -
lations is controlled by a retarder film.

# WAVEGUIDE-BASED DISPLAY SYSTEM

Background

[0001]        Display systems can used to make a desired image visible to a user (viewer). Wearable display systems can be embodied in a wearable headset which is arranged to display an image within a short distance from a human eye. Such wearable headsets are sometimes referred to as head mounted displays, and are provided with a frame which has a central portion fitting over a user's (wearer's) nose bridge and left and right support extensions which fit over a user's ears. Optical components are arranged in the frame so as to display an image within a few centimetres of the user's eyes. The image can be a computer generated image on a display, such as a micro display. The optical components are arranged to transport light of the desired image which is generated on the display to the user's eye to make the image visible to the user. The display on which the image is generated can form part of a light engine, such that the image itself generates collimated lights beams which can be guided by the optical component to provide an image visible to the user.

[0002]        Different kinds of optical components have been used to convey the image from the display to the human eye. These can include lenses, mirrors, optical waveguides, holograms and diffraction gratings, for example. In some display systems, the optical components are fabricated using optics that allows the user to see the image but not to see through this optics at the "real world". Other types of display systems provide view through this optics so that the generated image which is displayed to the user is overlaid onto a real world view. This is sometimes referred to as augmented reality.

[0003]        Waveguide-based display systems typically transport light from a light engine to the eye via a TIR (Total Internal Reflection) mechanism in a waveguide (light guide). Such systems can incorporate diffraction gratings, which cause effective beam expansion so as to output expanded versions of the beams provided by the light engine. This means the image is visible over a wider area when looking at the waveguide's output than when looking at the light engine directly: provided the eye is within an area such that it can receive some light from substantially all of the expanded beams, the whole image will be visible to the user. Such an area is referred to as an eye box.

[0004]        To maintain image quality, the structure of the waveguide can be configured in various ways to mitigate distortion of the transported light.

Summary

[0005]        According to one aspect of the present disclosure there is provided a display system comprising: a display on which an image is generated; an optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating; and collimating optics arranged to substantially collimate the image into multiple input beams, each beam formed by collimating light from a respective image point, that beam directed to the incoupling grating in a unique inward direction which depends on the location of that point in the image; wherein the intermediate and exit grating have widths substantially larger than the beams' diameters; wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating; wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating; wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form a virtual version of the image; and wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface.

[0006]        According to another aspect of the present disclosure there is provided an optical waveguide for a display system, the optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating, the incoupling grating arranged to receive multiple input beams, each beam formed by collimating light from a respective image point of an image, that beam directed to the incoupling grating in a unique inward direction which depends on the location of that point in the image; wherein the intermediate and exit grating have widths substantially larger than the beams' diameters; wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating; wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of that beam which are

coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating; wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form a virtual version of the image; and wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface.

[0007]    According to another aspect of the present disclosure there is provided a wearable headset comprising: a frame; a display mounted on the frame and on which an image is generated; an optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating; and collimating optics arranged to substantially collimate the image into multiple input beams, each beam formed by collimating light from a respective image point, that beam directed to the incoupling grating in a unique inward direction which depends on the location of that point in the image; wherein the intermediate and exit grating have widths substantially larger than the beams' diameters; wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating; wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating; wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form a virtual version of the image; and wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface.

[0008]    In the above described aspects of the present disclosure, a retardation pattern of the retarder film may be dynamically variable.

[0009]    This summary is provided to introduce a selection of concepts in a simplified form that are further described below in the detailed description. This summary is not

intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter. Nor is the claimed subject matter limited to implementations that solve any or all of the disadvantages noted in the background section.

Brief Description of Figures

[00010] Figure 1 shows a wearable display system;

[00011] Figure 2 shows a plan view of part of the display system;

[00012] Figures 3A and 3B shows perspective and frontal view of an optical component;

[00013] Figure 4A shows a schematic plan view of an optical component having a surface relief grating formed on its surface;

[00014] Figure 4B shows a schematic illustration of the optical component of figure 4A, shown interacting with incident light and viewed from the side;

[00015] Figure 5A shows a schematic illustration of a straight binary surface relief grating, shown interacting with incident light and viewed from the side;

[00016] Figure 5B shows a schematic illustration of a slanted binary surface relief grating, shown interacting with incident light and viewed from the side;

[00017] Figure 5C shows a schematic illustration of an overhanging triangular surface relief grating, shown interacting with incident light and viewed from the side;

[00018] Figure 6 shows a close up view of part of an incoupling zone of an optical component;

[00019] Figure 7A shows a perspective view of a part of a display system;

[00020] Figure 7B shows a plan view of individual pixels of a display;

[00021] Figure 7C and 7D show plan and frontal views of a beam interacting with an optical component;

[00022] Figure 7E shows a frontal view of an optical component performing beam expansion;

[00023] Figure 7F shows a plan view of an optical component performing beam expansion;

[00024] Figure 7G is a plan view of a curved optical component;

[00025] Figures 8A and 8B are plan and frontal views of a part of an optical component;

[00026]    Figure 9A shows a perspective view of beam reflection within a fold zone of a waveguide;

[00027]    Figure 9B illustrates a beam expansion mechanism;

[00028]    Figure 10 illustrates a banding effect that is observed in a virtual image by a wearer;

[00029]    Figure 11 shows a portion of the beam expansion mechanism shown in Figure 9B; and

[00030]    Figures 12 illustrates a retardation film attached to the optical component;

Detailed Description

[00031]    Figure 1 is a perspective view of a head mounted display. The head mounted display comprises a headpiece, which comprises a frame 2 having a central portion 4 intended to fit over the nose bridge of a wearer, and a left and right supporting extension 6,8 which are intended to fit over a user's ears. Although the supporting extensions are shown to be substantially straight, they could terminate with curved parts to more comfortably fit over the ears in the manner of conventional spectacles.

[00032]    The frame 2 supports left and right optical components, labelled 10L and 10R, which are waveguides. For ease of reference herein an optical component 10 (optical waveguide 10) will be considered to be either a left or right component, because the components are essentially identical apart from being mirror images of each other. Therefore, all description pertaining to the left-hand component also pertains to the right-hand component. The optical components will be described in more detail later with reference to Figure 3. The central portion 4 houses a light engine which is not shown in Figure 1 but which is shown in Figure 2.

[00033]    Figure 2 shows a plan view of a section of the top part of the frame of Figure 1. Thus, Figure 2 shows the light engine 13 which comprises a micro display 15 and imaging optics 17 in the form of a collimating lens 20. The light engine also includes a processor which is capable of generating an image for the micro display. The micro display can be any type of light of image source, such as liquid crystal on silicon (LCOS) displays, transmissive liquid crystal displays (LCD), matrix arrays of LED's (whether organic or inorganic) and any other suitable display. The display is driven by circuitry which is not visible in Figure 2 which activates individual pixels of the display to generate an image. The substantially collimated light, from each pixel, falls on an exit pupil 22 of the light engine 13. At exit pupil 22, collimated light beams are coupled into each optical component,

10L, 10R into a respective in-coupling zone 12L, 12R provided on each component. These in-coupling zones are clearly shown in Figure 1, but are not readily visible in Figure 2. In-coupled light is then guided, through a mechanism that involves diffraction and TIR, laterally of the optical component in a respective intermediate (fold) zone 14L, 14R, and also downward into a respective exit zone 16L, 16R where it exits the component 10 towards the users' eye. The zones 14L, 14R, 16L and 16R are shown in Figure 1. These mechanisms are described in detail below. Figure 2 shows a user's eye (right or left) receiving the diffracted light from an exit zone (16L or 16R). The output beam OB to a user's eye is parallel with the incident beam IB. See, for example, the incident beam marked IB in Figure 2 and two of the parallel output beams marked OB in Figure 2. The optical component 10 is located between the light engine 13 and the eye i.e. the display system configuration is of so-called transmissive type.

[00034]    Other headpieces are also within the scope of the subject matter. For instance, the display optics can equally be attached to the users head using a head band, helmet or other fit system. The purpose of the fit system is to support the display and provide stability to the display and other head borne systems such as tracking systems and cameras. The fit system will also be designed to meet user population in anthropometric range and head morphology and provide comfortable support of the display system.

[00035]    Beams from the same display 15 may be coupled into both components 10L, 10R so that an image is perceived by both eyes from a single display, or separate displays may be used to generate different images for each eye e.g. to provide a stereoscopic image. In alternative headsets, light engine(s) may be mounted at one or both of left and right portions of the frame - with the arrangement of the incoupling, fold and exit zones 12, 14, 16 flipped accordingly.

[00036]    The optical component 10 is substantially transparent such that a user can not only view the image from the light engine 13, but also can view a real world view through the optical component 10.

[00037]    The optical component 10 has a refractive index n which is such that total internal reflection takes place guiding the beam from the incoupling zone along the intermediate expansion zone 14, and down towards the exit zone 16.

[00038]    Figures 3A and 3B show an optical component in more detail.

[00039]    Figure 3A shows a perspective view of an optical component 10. The optical component is flat in that the front and rear portions of its surface are substantially flat (front

and rear defined from the viewpoint of the wearer, as indicated by the location of the eye in figure 3A). The front and rear portions of the surface are parallel to one another. The optical component 10 lies substantially in a plane (xy-plane), with the z axis (referred to as the "normal") directed towards the viewer from the optical component 10. The incoupling, fold and exit zones 12, 14 and 16 are shown, each defined by respective surface modulations 52, 46 and 56 on the surface of the optical component, which are on the rear of the waveguide from a viewpoint of the wearer. Each of the surface modulations 52, 46, 56 forms a respective surface relief grating (SRG), the nature of which will be described shortly. Instead of the SRGs, the holograms could be used providing the same optical function as the SRGs.

[00040]     As shown in the plan view of figure 3B, the fold zone has a horizontal extent W2 (referred to herein as the "width" of the expansion zone) in the lateral (x) direction and a vertical extent H2 (referred to herein as the "height" of the expansion zone) in the y direction which increases from the inner edge of the optical component to its outer edge in the lateral direction along its width W2. The exit zone has a horizontal extent W3 (width of the exit zone) and vertical extent H3 (height of the exit zone) which define the size of the eye box, which size is independent of the imaging optics in the light engine.

[00041]     Principles of the diffraction mechanisms which underlie operation of the head mounted display described herein will now be described with reference to figures 4A and 4B.

[00042]     The optical components described herein interact with light by way of reflection, refractions and diffraction. Diffraction occurs when a propagating wave interacts with a structure, such as an obstacle or slit. Diffraction can be described as the interference of waves and is most pronounced when that structure is comparable in size to the wavelength of the wave. Optical diffraction of visible light is due to the wave nature of light and can be described as the interference of light waves. Visible light has wavelengths between approximately 390 and 700 nanometres (nm) and diffraction of visible light is most pronounced when propagating light encounters structures of a similar scale e.g. of order 100 or 1000 nm in scale.

[00043]     One example of a diffractive structure is a periodic (substantially repeating) diffractive structure. Herein, a "diffraction grating" means any (part of) an optical component which has a periodic diffractive structure. Periodic structures can cause diffraction of light, which is typically most pronounced when the periodic structure has a

spatial period of similar size to the wavelength of the light. Types of periodic structures include, for instance, surface modulations on the surface of an optical component, refractive index modulations, holograms etc. When propagating light encounters the periodic structure, diffraction causes the light to be split into multiple beams in different directions. These directions depend on the wavelength of the light thus diffractions gratings cause dispersion of polychromatic (e.g. white) light, whereby the polychromatic light is split into different coloured beams travelling in different directions.

[00044]    When the period structure is on the surface of an optical component, it is referred to a surface grating. When the periodic structure is due to modulation of the surface itself, it is referred to as a surface relief grating (SRG). An example of a SRG is uniform straight grooves in a surface of an optical component that are separated by uniform straight groove spacing regions. Groove spacing regions are referred to herein as "lines", "grating lines" and "filling regions". The nature of the diffraction by a SRG depends both on the wavelength of light incident on the grating and various optical characteristics of the SRG, such as line spacing, groove depth and groove slant angle. An SRG can be fabricated by way of a suitable microfabrication process, which may involve etching of and/or deposition on a substrate to fabricate a desired periodic microstructure on the substrate. The substrate may be the optical component itself or a production master such as a mould for manufacturing optical components.

[00045]    Figures 4A and 4B show from the top and the side respectively part of a substantially transparent optical component 10 having an outer surface S. At least a portion of the surface S exhibits surface modulations that constitute a SRG 44 (e.g. 52, 54, 56), which is a microstructure. Such a portion is referred to as a "grating area".

[00046]    Figure 4B shows the optical component 10, and in particular the SRG 44, interacting with an incoming illuminating light beam I that is inwardly incident on the SRG 44. The light I is white light in this example, and thus has multiple colour components. The light I interacts with the SRG 44 which splits the light into several beams directed inwardly into the optical component 10. Some of the light I may also be reflected back from the surface S as a reflected beam R0. A zero-order mode inward beam T0 and any reflection R0 are created in accordance with the normal principles of diffraction as well as other non-zero-order (±n-order) modes (which can be explained as wave interference). Figure 4B shows first-order inward beams Tl, T-l; it will be appreciated that higher-order beams may or may not also be created depending on the configuration of the optical component 10.

Because the nature of the diffraction is dependent on wavelength, for higher-order modes, different colour components (i.e. wavelength components) of the incident light I are, when present, split into beams of different colours at different angles of propagation relative to one another as illustrated in figure 4B.

[00047]     Figures 5A-5C are close-up schematic cross sectional views of different exemplary SRGs 44a- 44c (collectively referenced as 44 herein) that may formed by modulation of the surface S of the optical component 10 (which is viewed from the side in these figures). Light beams are denoted as arrows whose thicknesses denote approximate relative intensity (with higher intensity beams shown as thicker arrows).

[00048]     Figure 5A shows an example of a straight binary SRG 44a. The straight binary SRG 44a is formed of a series of grooves 7a in the surface S separated by protruding groove spacing regions 9a which are also referred to herein as "filling regions", "grating lines" or simply "lines". The SRG 44a has a spatial period of d (referred to as the "grating period"), which is the distance over which the modulations' shape repeats and which is thus the distance between adjacent lines/grooves. The grooves 7a have a depth h and have substantially straight walls and substantially flat bases. The filling regions have a height h and a width that is substantially uniform over the height h of the filling regions, labelled "w" in figure 2 (with w being some fraction f of the period: w=f*d).

[00049]     For a straight binary SRG, the walls are substantially perpendicular to the surface S. For this reason, the SRG 44a causes symmetric diffraction of incident light I that is entering perpendicularly to the surface, in that each +n-order mode beam (e.g. Tl) created by the SRG 4a has substantially the same intensity as the corresponding -n-order mode beam (e.g. T-l), typically less than about one fifth (0.2) of the intensity of the incident beam I.

[00050]     Figure 5B shows an example of a slanted binary SRG 44b. The slanted binary SRG 44b is also formed of grooves, labelled 7b, in the surface S having substantially straight walls and substantially flat bases separated by lines 9b of width w. However, in contrast to the straight SRG 44a, the walls are slanted by an amount relative to the normal, denoted by the angle a in figure 25B. The grooves 7b have a depth h as measured along the normal. Due to the asymmetry introduced by the non-zero slant, in-order mode inward beams travelling away from the slant direction have greater intensity that their +n-order mode counterparts (e.g. in the example of figure 5B, the Tl beam is directed away from the direction of slant and has usually greater intensity than the T-l beam, though this depends on e.g. the grating period d); by increasing the slant by a sufficient amount, those $\mp$n

counterparts can be substantially eliminated (i.e. to have substantially zero intensity). The intensity of the T O beam is typically also very much reduced by a slanted binary SRG such that, in the example of figure 5B, the first-order beam Tl typically has an intensity of at most about four fifths (0.8) the intensity of the incident beam I.

[00051]     The binary SRGs 44a and 44b can be viewed as spatial waveforms embedded in the surface S that have a substantially square wave shape (with period d). In the case of the SRG 44b, the shape is a skewed square wave shape skewed by a .

[00052]     Figure 5C shows an example of an overhanging triangular SRG 44c which is a special case of an overhanging trapezoidal SRG. The triangular SRG 44c is formed of grooves 7c in the surface S that are triangular in shape (and which thus have discernible tips) and which have a depth h as measured along the normal. Filling regions 9c take the form of triangular, tooth-like protrusions (teeth), having medians that make an angle a with the normal (a being the slant angle of the SRG 44c). The teeth have tips that are separated by d (which is the grating period of the SRG 44c), a width that is w at the base of the teeth and which narrows to substantially zero at the tips of the teeth. For the SRG of figure 44c, w~d, but generally can be w<d. The SRG is overhanging in that the tips of the teeth extend over the tips of the grooves. It is possible to construct overhanging triangular SRGs that substantially eliminate both the transmission-mode T O beam and the +n-mode beams, leaving only in-order  mode beams (e.g. only Tl). The grooves have walls which are at an angle *y* to the median (wall angle).

[00053]     The SRG 44c can be viewed as a spatial waveform embedded in S that has a substantially triangular wave shape, which is skewed by a .

[00054]     Other SRGs are also possible, for example other types of trapezoidal SRGs (which may not narrow in width all the way to zero), sinusoidal SRGs etc. Such other SRGs also exhibit depth h, linewidth w, slant angle a and wall angles γ which can be defined in a similar manner to figure 5A-C.

[00055]     In the present display system, d is typically between about 250 and 500 nm, and h between about 30 and 400 nm. The slant angle a is typically between about 0 and 45 degrees (such that slant direction is typically elevated above the surface S by an amount between about 45 and 90 degrees).

[00056]     An SRG has a diffraction efficiency defined in terms of the intensity of desired diffracted beam(s) (e.g. Tl) relative to the intensity of the illuminating beam I, and can be expressed as a ratio η of those intensities. As will be apparent from the above, slanted

binary SRGs can achieve higher efficiency (e.g. 4b - up to η~0.8 if Tl is the desired beam) than non-slanted SRGs (e.g. 44a - only up to about η~0.2 if Tl is the desired beam). With overhanging triangular SRGs, it is possible to achieve near-optimal efficiencies of η~1.

[00057]     Returning to figures 3A and 3B, it can be seen that the incoupling, fold and exit zones 12, 14, 16 are diffraction gratings whose periodic structure arises due to the modulations 52, 54, 56 of the optical component's surface that form the incoupling, fold and exit SRGs respectively, and which cover the incoupling, fold and exit zones 12, 14, 16 respectively.

[00058]     Figure 6 shows the incoupling SRG 52 with greater clarity, including an expanded version showing how the light beam interacts with it. Figure 6 shows a plan view of the optical component 10. The light engine 13 provides beams of collimated light, one of which is shown (corresponding to a display pixel). That beam falls on the incoupling SRG 52 and thus causes total internal reflection of the beam in the component 10. The intermediate grating 14 directs versions of the beams down to the exit grating 16, which causes diffraction of the image onto the user's eye. The operation of the grating 12 is shown in more detail in the expanded portion which shows rays of the incoming light beam coming in from the left and denoted I and those rays being diffracted so as to undergo TIR in the optical component 10. The grating in Figure 6 is of the type shown in Figure 5B but could also be of the type shown in figure 5C or some other slanted grating shape.

[00059]     Optical principles underlying certain embodiments will now be described with reference to figures 7A-9B.

[00060]     Figure 7a shows a perspective view of the display 15, imaging optics 17 and incoupling SRG 52. Different geometric points on the region of the display 15 on which an image is displayed are referred to herein as image points, which may be active (currently emitting light) or inactive (not currently emitting light). In practice, individual pixels can be approximated as image points.

[00061]     The imaging optics 17 can typically be approximated as a principal plane (thin lens approximation) or, in some cases, more accurately as a pair of principal planes (thick lens approximation) the location(s) of which are determined by the nature and arrangement of its constituent lenses 24, 20 (not shown individually in figure 7a). In these approximations, any refraction caused by the imaging optics 17 is approximated as occurring at the principal plane(s). To avoid unnecessary complication, principles of various embodiments will be described in relation to a thin lens approximation of the

imaging optics 17, and thus in relation to a single principal plane labelled 31 in figure 7a, but it will be apparent that more complex imaging optics that do not fit this approximation still can be utilized to achieve the desired effects.

[00062]      The imaging optics 17 has an optical axis 30 and a front focal point, and is positioned relative to the optical component 10 so that the optical axis 30 intersects the incoupling SRG 52 at or near the geometric centre of the incoupling SRG 52 with the front focal point lying substantially at an image point $\mathbf{X_o}$ on the display (that is, lying in the same plane as the front of the display). Another arbitrary image point $\mathbf{X}$ on the display is shown, and principles underlying various embodiments will now be described in relation to $\mathbf{X}$ without loss of generality. In the following, the terminology "for each $\mathbf{X}$" or similar is used as a convenient shorthand to mean "for each image point (including $\mathbf{X}$)" or similar, as will be apparent in context.

[00063]      When active, image points - including the image point labelled $\mathbf{X}$ and $\mathbf{X_o}$ - act as individual illumination point sources from which light propagates in a substantially isotropic manner through the half-space forward of the display 15. Image points in areas of the image perceived as lighter emit light of higher intensity relative to areas of the image perceived as darker. Image points in areas perceived as black emit no or only very low intensity light (inactive image points). The intensity of the light emitted by a particular image point may change as the image changes, for instance when a video is displayed on the display 15.

[00064]      Each active image point provides substantially uniform illumination of a collimating area A of the imaging optics 17, which is substantially circular and has a diameter D that depends on factors such as the diameters of the constituent lenses (D may be of order 1-lOmm, but this is just an example). This is illustrated for the image point $\mathbf{X}$ in figure 7a, which shows how any propagating light within a cone $\mathbf{32(X)}$ from $\mathbf{X}$ is incident on the collimating area A. The imaging optics collimates any light $\mathbf{32(X)}$ incident on the collimating area A to form a collimated beam $\mathbf{34(X)}$ of diameter D (input beam), which is directed towards the incoupling grating 52 of the optical component 10. The beam $\mathbf{34(X)}$ is thus incident on the incoupling grating 52. A shielding component (not shown) may be arranged to prevent any un-collimated light from outside of the cone $\mathbf{32(X)}$ that is emitted from $\mathbf{X}$ from reaching the optical component 10.

[00065]      The beam $\mathbf{34(X)}$ corresponding to the image point $\mathbf{X}$ is directed in an inward propagation direction towards the incoupling SRG 52, which can be described by a

propagation vector $\widehat{k}_{in}(X)$ (herein, bold typeface is used to denote 3-dimensional vectors, with hats on such vectors indicating denoting a unit vector). The inward propagation direction depends on the location of X in the image and, moreover, is unique to X. That unique propagation direction can be parameterized in terms of an azimuthal angle $\phi_{in}(X)$ (which is the angle between the x-axis and the projection of $\widehat{k}_{in}(X)$ in the xy-plane) and a polar angle $\theta_{in}(X)$ (which is the angle between the z-axis and $\widehat{k}_{in}(P)$ as measured in the plane in which both the z-axis and $\widehat{k}_{in}(X)$ lie - note this is not the xz-plane in general). The notation $\phi_{in}(X)$, $\theta_{in}(X)$ is adopted to denote the aforementioned dependence on X; as indicated $\phi_{in}(X)$, $\theta_{in}(X)$ are unique to that X. Note that, herein, both such unit vectors and such polar/azimuthal angle pairs parameterizing such vectors are sometimes referred herein to as "directions" (as the latter represent complete parameterizations thereof), and that sometimes azimuthal angles are referred to in isolation as xy-directions for the same reason. Note further that "inward" is used herein to refer to propagation that is towards the waveguide (having a positive z-component when propagation is towards the rear of the waveguide as perceived by the viewer and a negative z-component when propagation is towards the front of the waveguide).

[00066]      The imaging optics has a principle point P, which is the point at which the optical axis 30 intersects the principal plane 31 and which typically lies at or near the centre of the collimation area A. The inward direction $\widehat{k}_{in}(X)$ and the optical axis 30 have an angular separation $\beta(X)$ equal to the angle subtended by X and $X_0$ from P. $\beta(X)=\theta_{in}(X)$ if the optical axis is parallel to the z-axis (which is not necessarily the case).

[00067]      As will be apparent, the above applies for each active image point and the imaging optics is thus arranged to substantially collimate the image which is currently on the display 15 into multiple input beams, each corresponding to and propagating in a unique direction determined by the location of a respective active image point (active pixel in practice). That is, the imaging optics 17 effectively converts each active point source X into a collimated beam in a unique inward direction $\widehat{k}_{in}(X)$. As will be apparent, this can be equivalently stated as the various input beams for all the active image points forming a virtual image at infinity that corresponds to the real image that is currently on the display 17. A virtual image of this nature is sometimes referred to herein as a virtual version of the image (or similar).

[00068]       The input beam corresponding to the image point Xo (not shown) would propagate parallel to the optical axis 30, towards or near the geometric centre of the incoupling SRG 52.

[00069]       As mentioned, in practice, individual pixels of the display 15 can be approximated as single image points. This is illustrated in figure 7B which is a schematic plan view showing the principal plane 31 and two adjacent pixels Xa, Xb of the display 15, whose centres subtend an angle $\Delta\beta$ from the principal point P. Light emitted the pixels Xa, Xb when active is effectively converted into collimated beams 34(Xa), 34(Xb) having an angular separation equal to $\Delta\beta$. As will be apparent, the scale of the pixels Xa, Xb has been greatly enlarged for the purposes of illustration.

[00070]       The beams are highly collimated and are highly parallel to one another, exhibiting overall angular variation no greater (and potentially significantly less) than the angle subtended by an individual pixel from P ($\sim\Delta\beta$) e.g. typically having an angular range no more than about 1/2 milliradian. As will become apparent in view of the following, this increases the image quality of the final image as perceived by the wearer.

[00071]       Figures 7C and 7D show schematic plan (xz) and frontal (yz) views of part of the optical component respectively. As indicated in these figures, the incoupling grating 52 causes diffraction of the beam 34(X) thereby causing a first ($\pm 1$) order mode beam to propagate within the optical component 10 in a new direction $\widehat{k}(X)$ that is generally towards the fold SRG 54 (i.e. that has a positive x-component). The new direction $\widehat{k}(X)$ can be parameterized by azimuthal and polar angles $\phi(X)$ - where $|\phi(X)| \leq |\phi_{in}(X)|$ and $\Theta(X)$ - where $|\theta(X)| > |\theta_{in}(X)|$ - which are also determined by the location of and unique to the image point X. The grating 52 is configured so that the first order mode is the only significant diffraction mode, with the intensity of this new beam thus substantially matching that of the input beam. As mentioned above, a slanted grating can be used to achieve this desired effect (the beam as directed away from the incoupling SRG 52 would correspond, for instance, to beam Tl as shown in figures 4B or 4C). In this manner, the beam 34(X) is coupled into the incoupling zone 12 of the optical component 10 in the new direction $\widehat{k}(X)$.

[00072]       The optical component has a refractive index n and is configured such that the polar angle $\Theta(X)$ satisfies total internal reflection criteria given by:

(1): $\sin\theta(X) > 1/n$   for each X.

As will be apparent, each beam input from the imaging optics 17 thus propagates through the optical component 10 by way of total internal reflection (TIR) in a generally horizontal

(+x) direction (offset from the x-axis by $\phi(X) < \phi_{in}(X)$). In this manner, the beam 34(X) is coupled from the incoupling zone 12 into the fold zone 14, in which it propagates along the width of the fold zone 14.

[00073]     Figure 7E shows 10 a frontal (xy) view of the whole of the optical component 10, from a viewpoint similar to that of the wearer. As explained in more detail below, a combination of diffractive beam splitting and total internal reflection within the optical component 10 results in multiple versions of each input beam 34(X) being outwardly diffracted from the exit SRG along both the width and the height of the exit zone 16 as output beams 38(X) in respective outward directions (that is, away from the optical component 10) that substantially match the respective inward direction $\widehat{k}_{in}(X)$ of the corresponding input beam 34(X).

[00074]     In Figure 7E, beams external to the optical component 10 are represented using shading and dotted lines are used to represent beams within the optical component 10. Perspective is used to indicate propagation in the z-direction, with widening (resp. narrowing) of the beams in figure 7E representing propagation in the positive (resp. negative) z direction; that is towards (resp. away from) the wearer. Thus, diverging dotted lines represent beams within the optical component 10 propagating towards the front wall of the optical component 10; the widest parts represent those beams striking the front wall of the optical component 10, from which they are totally internally reflected back towards the rear wall (on which the various SRGs are formed), which is represented by the dotted lines converging from the widest points to the narrowest points at which they are incident on the rear wall. Regions where the various beams are incident on the fold and exit SRGs are labelled S and E and termed splitting and exit regions respectively for reasons that will become apparent.

[00075]     As illustrated, the input beam 34(X) is coupled into the waveguide by way of the aforementioned diffraction by the incoupling SRG 52, and propagates along the width of the incoupling zone 12 by way of TIR in the direction $\phi(X), \pm\Theta(X)$ (the sign but not the magnitude of the polar angle changing whenever the beam is reflected). As will be apparent, this results in the beam 34(X) eventually striking the fold SRG at the left-most splitting region S.

[00076]     When the beam 34(X) is incident at a splitting region S, that incident beam 34(X) is effectively split in two by way of diffraction to create a new version of that beam 42(X) (specifically a -1 reflection mode beam) which directed in a specific and generally

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downwards (-y) direction $\phi'(X)$, $\pm\Theta(X)$ towards the exit zone 16 due to the fold SRG 54 having a particular configuration which will be described in due course, in addition to a zero order reflection mode beam (specular reflection beam), which continues to propagate along the width of the beam in the same direction $\phi(X)$, $\pm\Theta(X)$ just as the beam 34(X) would in the absence of the fold SRG (albeit at a reduced intensity). Thus, the beam 34(X) effectively continues propagates along substantially the whole width of the fold zone 14, striking the fold SRG at various splitting regions S, with another new version of the beam (in the same specific downward direction $\phi'(X)$, $\pm\Theta(X)$) created at each splitting region S. As shown in figure 7E, this results in multiple versions of the beam 34(X) being coupled into the exit zone 16, which are horizontally separated so as to collectively span substantially the width of the exit zone 16.

[00077]    As also shown in figure 7E, a new version 42(X) of the beam as created at a splitting region S may itself strike the fold SRG during its downward propagation. This will result in a zero order mode being created which continues to propagate generally downwards in the direction $\phi'(X)$, $\pm\Theta(X)$ and which can be viewed as continued propagation of that beam, but may also result in a non-zero order mode beam 40(X) (further new version) being created by way of diffraction. However, any such beam 40(X) created by way of such double diffraction at the same SRG will propagate in substantially the same direction $\phi(X)$, $\pm\Theta(X)$ along the width of the fold zone 14 as the original beam 34(X) as coupled into the optical component 10 (see below). Thus, notwithstanding the possibility of multiple diffractions by the fold SRG, propagation of the various versions of the beam 34(X) (corresponding to image point X) within the optical component 10 is effectively limited to two xy-directions: the generally horizontal direction ($\phi(X)$, $\pm\Theta(X)$), and the specific and generally downward direction ($\phi'(X)$, $\pm\Theta(X)$) that will be discussed shortly.

[00078]    Propagation within the fold zone 14 is thus highly regular, with all beam versions corresponding to a particular image point X substantially constrained to a lattice like structure in the manner illustrated.

[00079]    The exit zone 16 is located below the fold zone 14 and thus the downward-propagating versions of the beam 42(X) are coupled into the exit zone 16, in which they are guided onto the various exit regions E of the output SRG. The exit SRG 56 is configured so as, when a version of the beam strikes the output SRG, that beam is diffracted to create a first order mode beam directed outwardly from the exit SRG 56 in an outward direction that substantially matches the unique inward direction in which the original beam 34(X)

corresponding to image point X was inputted. Because there are multiple versions of the beam propagating downwards that are substantially span the width of the exit zone 16, multiple output beams are generated across the width of the exit zone 16 (as shown in figure 7E) to provide effective horizontal beam expansion.

[00080]        Moreover, the exit SRG 56 is configured so that, in addition to the outwardly diffracted beams 38(X) being created at the various exit regions E from an incident beam, a zero order diffraction mode beam continuous to propagate downwards in the same specific direction as that incident beam. This, in turn, strikes the exit SRG at a lower exit zone 16s in the manner illustrated in figure 7E, resulting in both continuing zero-order and outward first order beams. Thus, multiple output beams 38(X) are also generated across substantially the height of the exit zone 16 to provide effective vertical beam expansion.

[00081]        The output beams 38(X) are directed outwardly in outward directions that substantially match the unique input direction in which the original beam 34(X) is inputted. In this context, substantially matching means that the outward direction is related to the input direction in a manner that enables the wearer's eye to focus any combination of the output beams 38(X) to a single point on the retina, thus reconstructing the image point X (see below).

[00082]        For a flat optical component (that is, whose front and rear surfaces lie substantially parallel to the xy-plane in their entirety), the output beams are substantially parallel to one another (to at least within the angle $\Delta\beta$ subtended by two adjacent display pixels) and propagate outwardly in an output propagation direction $\widehat{k}_{0\mathrm{ut}}(X)$ that is parallel to the unique inward direction $\widehat{k}_{in}(X)$ in which the corresponding input beam 34(X) was directed to the incoupling SRG 52. That is, directing the beam 34(X) corresponding to the image point X to the incoupling SRG 52 in the inward direction $\widehat{k}_{in}(X)$ causes corresponding output beams 38(X) to be diffracted outwardly and in parallel from the exit zone 16, each in an outward propagation direction $\widehat{k}_{0Ut}(X) = \widehat{k}_{in}(X)$ due to the configuration of the various SRGs (see below).

[00083]        As will now be described with reference to figure 7F, this enables a viewer's eye to reconstruct the image when looking at the exit zone 16. Figure 7F shows a plan (xz) view of the optical component 10. The input beam 34(X) is in coupled to the optical component 10 resulting in multiple parallel output beams 38(X) being created at the various exit regions E in the manner discussed above. This can be equivalently expressed at the

various output beams corresponding to all the image points forming the same virtual image (at infinity) as the corresponding input beams.

[00084]     Because the beams 38(X) corresponding to the image point X are all substantially parallel, any light of one or more of the beam(s) 38(X) which is received by the eye 37 is focussed as if the eye 37 were perceiving an image at infinity (i.e. a distant image). The eye 37 thus focuses such received light onto a single retina point, just as if the light were being received from the imaging optics 17 directly, thus reconstructing the image point X (e.g. pixel) ion the retina. As will be apparent, the same is true of each active image point (e.g. pixel) so that the eye 37 reconstructs the whole image that is currently on the display 15.

[00085]     However, in contrast to receiving the image directly from the optics 17 - from which only a respective single beam 34(X) of diameter D is emitted for each X - the output beams 39(X) are emitted over a significantly wider area i.e. substantially that of the exit zone 16, which is substantially larger than the area of the inputted beam (~$D^2$). It does not matter which (parts) of the beam(s) 38(X) the eye receives as all are focused to the same retina point - e.g., were the eye 37 to be moved horizontally (±x) in figure 7F, it is apparent that the image will still be perceived. Thus, no adaptation of the display system is required for, say, viewers with different pupillary distances beyond making the exit zone 16 wide enough to anticipate a reasonable range of pupillary distances: whilst viewers whose eyes are closer together will generally receive light from the side of the exit zone 16 nearer the incoupling zone 12 as compared with viewers whose eyes are further apart, both will nonetheless perceive the same image. Moreover, as the eye 27 rotates, different parts of the image are brought towards the centre of the viewer's field of vision (as the angle of the beams relative to the optical axis of the eye changes) with the image still remaining visible, thereby allowing the viewer to focus their attention on different parts of the image as desired.

[00086]     The same relative angular separation Δβ exhibited the input beams corresponding any two adjacent pixels Xa, Xb is also exhibited by the corresponding sets of output beams 38(Xa), 38(Xb) - thus adjacent pixels are focused to adjacent retina points by the eye 37. All the various versions of the beam remain highly collimated as they propagate through the optical component 10, preventing significant overlap of pixel images as focused on the retina, thereby preserving image sharpness.

[00087]     It should be noted that figures 7A-7G are not to scale and that in particular beams diameters are, for the sake of clarity, generally reduced relative to components such as the display 15 than would typically be expected in practice.

[00088]     The configuration of the incoupling SRG 52 will now be described with reference to figures 8A and 8B, which show schematic plan and frontal views of part of the fold grating 52. Note, in figures 8A and 8B, beams are represented by arrows (that is, their area is not represented) for the sake of clarity.

[00089]     Figure 8A shows two image points XL, XR located at the far left and far right of the display 15 respectively, from which light is collimated by the optics 17 to generate respective input beams 34(XL), 34(XR) in inward directions $(0_{in}(\mathbf{XL}), \varphi_{in}(\mathbf{XL}))$, $(0_{in}(\mathbf{XR}), \varphi_{in}(\mathbf{XR}))$. These beams are coupled into the optical component 10 by the incoupling SRG 52 as shown - the incoupled beams shown created at the incoupling SRG 52 are first order (+1) mode beams created by way of diffraction of the beams incident on the SRG 52. The beams 34(XL), 34(XR) as coupled into the waveguide propagate in directions defined by the polar angles $0(XL)$, $0(XR)$.

[00090]     Figure 8B shows two image points XRl and XR2 at the far top-right and far bottom-right of the display 15. Note in this figure dashed-dotted lines denote aspects which are behind the optical component 10 (-z). Corresponding beams 34(XL), 34(XR) in directions within the optical component 10 with polar angles $(|)(XL)$, $(|)(XR)$.

Such angles $\Theta(X)$, $\phi(X)$ are given by the (transmissive) grating equations:

$$n \sin \Theta(X) \sin \phi(X) = \sin \theta_{i\eta}(X) \sin 0_{in}(X) \qquad \textbf{(2)}$$

$$\boldsymbol{n} \sin \Theta(X) \cos \phi(X) = \sin \theta_{i\eta}(X) \cos \phi_{in}(X) + \frac{\lambda}{d_1} \qquad (3)$$

with the SRG 52 having a grating period $d_1$, the beam light having a wavelength $\lambda$, and n the refractive index of the optical component.

[00091]     It is straightforward to show from (2), (3) that $0(XL)= 0_{max}$ and $0(XR)= 0_{min}$ i.e. that any beam as coupled into the component 10 propagates with an initial polar angle in the range $[0(XR), 0(XL)]$; and that $\phi(XR2)= \phi_{max}$ and $\phi(XR1)= \phi_{min}$ $(\approx -\phi_{max}$ in this example) i.e. that any beam as coupled into the component initially propagates with an azimuthal angle in the range $|>(XR1), \phi(XR2)]$ $( \approx H(XR2), \phi(XR2)])$.

[00092]     The configuration of the fold SRG 54 will now be described with references to figures 9A-9B. Note, in figures 9A and 9B, beams are again represented by arrows, without any representation of their areas, for the sake of clarity. In these figures, dotted

lines denote orientations perpendicular to the fold SRG grating lines, dashed lines denote orientations perpendicular to the incoupling SRG grating lines, and dash-dotted lines denote orientations perpendicular to the exit SRG grating lines.

[00093]     Figure 9A shows a perspective view of the beam 34(X) as coupled into the fold zone 14 of the optical component 10, having been reflected from the front wall of the optical component 10 and thus travelling in the direction $(\phi(X), -\Theta(X))$ towards the fold SRG 54.  A dotted line (which lies perpendicular to the fold SRG grating lines) is shown to represent the orientation of the fold SRG.

[00094]     The fold SRG 54 and incoupling SRG 52 have a relative orientation angle A (which is the angle between their respective grating lines).  The beam thus makes an angle $A+\phi(X)$ (see figure 9B) with the fold SRG grating lines as measured in the xy-plane.  The beam 34 is incident on the fold SRG 54, which diffracts the beam 34 into different components.  A zero order reflection mode (specular reflection) beam is created which continues to propagate in the direction $(\phi(X), +\Theta(X))$ just as the beam 34(X) would due to reflection in the absence of the fold SRG 54 (albeit at a reduced intensity).  This specular reflection beam can be viewed as effectively a continuation of the beam 34(X) and for this reason is also labelled 34(X).  A first order (-1) reflection mode beam 42(X) is also created which can be effectively considered a new version of the beam.

[00095]     As indicated, the new version of the beam 42(X) propagates in a specific direction $(\phi'(X), \Theta(X))$ which is given by the known (reflective) grating equations:

$$n \sin \Theta'(X) \sin(A + \phi'(X)) = n \sin \Theta(X) \sin(A + \phi(X)) \qquad (4)$$

$$n \sin \theta'(X) \cos(A + 0'(X)) = n \sin \Theta(X) \cos(A + \phi(X)) - \frac{A}{d_2} \qquad (5)$$

where the fold SRG has a grating period $d_2$, the beam light has a wavelength $\lambda$ and n is the refractive index of the optical component 10.

[00096]     As shown in figure 9B, which shows a schematic frontal view of the optical component 10, the beam 34(X) is coupled into the incoupling zone 12 with azimuthal angle $\phi(X)$ and thus makes an xy-angle $\phi(X)+A$ the fold SRG 54.

[00097]     A first new version 42a(X) (-1 mode) of the beam 34(X) is created when it is first diffracted by the fold SRG 54 and a second new version 42b(X) (-1 mode) when it is next diffracted by the fold SRG 54 (and so on), which both propagate in xy-direction $\phi'(X)$. In this manner, the beam 34(X) is effectively split into multiple versions, which are horizontally separated (across the width of the fold zone 14).  These are directed down

towards the exit zone 16 and thus coupled into the exit zone 16 (across substantially the width of the exit zone 16 due to the horizontal separation). As can be see, the multiple versions are thus incident on the various exit regions (labelled E) of the exit SRG 56, which lie along the width of the exit zone 16.

[00098]    These new, downward-propagating versions (in the $\phi'(X)$ direction) may themselves meet the fold SRG once again, as illustrated. However, it can be shown from (4), (5) that any first order reflection mode beam (e.g. 40a(X), +1 mode) created by diffraction at an SRG of an incident beam (e.g. 42a(X), -1 mode) which is itself a first order reflection mode beam created by an earlier diffraction of an original beam (e.g. 34(X)) at the same SRG will revert to the direction of the original beam (e.g. $\phi(X)$, $\pm\Theta(X)$, which is the direction of propagation of 40a(X)). Thus, propagation within the fold zone 14 is restricted to a diamond-like lattice, as can be seen from the geometry of figure 9B. The beam labelled 42ab(X) is a superposition of a specular reflection beam created when 42b(X) meets the fold SRG 54 and a -1 mode beam created when 40a(X) meets the fold SRG at substantially the same location; the beam labelled 42ab(X) is a superposition of a specular reflection beam created when 40a(X) meets the fold SRG 54 and a +1 mode beam created when 42b(X) meets the fold SRG at substantially the same location (and so on).

[00099]    The exit SRG and incoupling SRG 52, 56 are oriented with a relative orientation angle A' (which is the angle between their respective grating lines). At each of the exit regions, the version meeting that region is diffracted so that, in addition to a zero order reflection mode beam propagating downwards in the direction $\phi'(X)$, $\pm\Theta(X)$, a first order (+1) transmission mode beam 38(X) which propagates away from the optical component 10 in an outward direction $\phi_{out}(X)$, $\theta_{out}(X)$ given by:

$$\sin \theta_{0\text{ut}}(X) \sin(A' + \phi_{\text{ou}_i}(X)) = n \sin \Theta'(X) \sin(A' + \phi'(X)) \qquad (6)$$

$$\sin 0_{o\text{ut}}(X) \cos(A' + \phi_{0\text{ut}}(X)) = n \sin \Theta'(X) \cos(A' + \phi'(X)) + \frac{A}{\vec{\alpha}_3} \qquad (7)$$

The output direction $\theta_{out}(X)$, $\phi_{\text{ou}_i}(X)$ is that of the output beams outside of the waveguide (propagating in air). For a flat waveguide, equations (6), (7) hold both when the exit grating is on the front of the waveguide - in which case the output beams are first order transmission mode beams (as can be seen, equations (6), (7) correspond to the known transmission grating equations) - but also when the exit grating is on the rear of the waveguide (as in figure 7F) - in which case the output beams correspond to first order reflection mode beams which, upon initial reflection from the rear exit grating propagate in a direction $\theta'_{0\text{ut}}(X)$, $\phi'_{\text{out}}(X)$ within the optical component 10 given by:

$$n \sin 0'_{out}(X) \sin(A' + \phi'_{out}(X)) = n \sin \Theta'(X) \sin(A' + \phi'(X)) \qquad \textbf{(6')}$$

$$n \sin \theta'_{out}(X) \cos(A' + \phi'_{out}(X)) = n \sin 0'(*) \cos(A' + \phi'(X)) + \frac{\lambda}{d'_3} \qquad \textbf{(7')};$$

these beams are then refracted at the front surface of the optical component, and thus exit the optical component in a direction $\theta_{in}$ (X), $\phi_{in}(X)$ given by Snell's law:

$$\sin \theta_{out}(X) = n \sin \theta'_{out}(X) \qquad \textbf{(8)}$$

$$\phi'_{out}(X) = \phi_{out}(X) \qquad \textbf{(9)}$$

As will be apparent, the conditions of equations (6), (7) follow straight forwardly from (6'),(7'),(8) and (9). Note that such refraction at the front surface, whilst not readily visible in figure 7F, will nonetheless occur in the arrangement of figure 7F.

It can be shown from the equations (2-7) that, when

$$d = d_1 = d_3 \qquad \textbf{(10)}$$

(that is, when the periods of the incoupling and exit SRGs 52, 56 substantially match);

$$d_2 = d/(2 \cos A); \qquad \textbf{(11)}$$

and

$$A' = 2A; \qquad \textbf{(12)}$$

then $(0_{out}(X), \phi_{out}(X)) = (\theta_{in}(X), \phi_{in}(X))$.

Moreover, when the condition

$$\sqrt{(1 + 8 \cos^2 A)} > \frac{nd}{\lambda} \qquad \textbf{(13)}$$

is met, no modes besides the above-mentioned first order and zero order reflection modes are created by diffraction at the fold SRG 54. That is, no additional undesired beams are created in the fold zone when this criteria is met. The condition (13) is met for a large range of A, from about 0 to 70 degrees.

[000100]     In other words, when these criteria are met, the exit SRG 56 effectively acts as an inverse to the incoupling SRG 52, reversing the effect of the incoupling SRG diffraction for each version of the beam with which it interacts, thereby outputting what is effectively a two-dimensionally expanded version of that beam 34(X) having an area substantially that of the exit SRG 56 ($\gg D^2$ and which, as noted, is independent of the imaging optics 17) in the same direction as the original beam was inputted to the component 10 so that the outwardly diffracted beams form substantially the same virtual image as the inwardly inputted beams but which is perceivable over a much larger area.

[000101]     In the example of figure 9B, A ≈ 45° i.e. so that the fold SRG and exit SRGs 54, 56 are oriented at substantially 45 and 90 degrees to the incoupling SRG 52 respectively,

with the grating period of the fold region $d_2 = \mathbf{d/V2}.$ However, this is only an example and, in fact, the overall efficiency of the display system is typically increased when A ≥ 50°.

[000102]     The above considers flat optical components, but a suitably curved optical component (that is, having a radius of curvature extending substantially along the z direction) can be configured to function as an effective lens such that the output beams 30(X) are and are no longer as highly collimated and are not parallel, but have specific relative direction and angular separations such that each traces back to a common point of convergence - this is illustrated in figure 7G, in which the common point of convergence is labelled Q. Moreover, when every image point is considered, the various points of convergence for all the different active image points lie in substantially the same plane, labelled 50, located a distance L from the eye 37 so that the eye 37 can focus accordingly to perceive the whole image as if it were the distance L away. This can be equivalently stated as the various output beams forming substantially the same virtual version of the current display image as the corresponding input beams, but at the distance L from the eye 37 rather than at infinity. Curved optical components may be particularly suitable for short-sighted eyes unable to properly focus distant images.

[000103]     Note, in general the "width" of the fold and exit zones does not have to be their horizontal extent- in general, the width of a fold or exit zone 14, 16 is that zone's extent in the general direction in which light is coupled into the fold zone 14 from the incoupling zone 12 (which is horizontal in the above examples, but more generally is a direction substantially perpendicular to the grating lines of the incoupling zone 12).

[000104]     Note that the above arrangement of the light engine 13 is just an example. For example, an alternative light engine based on so-called scanning can provide a single beam, the orientation of which is fast modulated whilst simultaneously modulating its intensity and/or colour. As will be apparent, a virtual image can be simulated in this manner that is equivalent to a virtual image that would be created by collimating light of a (real) image on a display with collimating optics.

[000105]     As is well known to persons skilled in the art, the modular transfer function (MTF) is a measure of the ability of an optical system to transfer various levels of detail from object to image. An MTF of 1.0 (or 100%) represents perfect contrast preservation, whereas values less than this mean that more and more contrast is being lost - until an MTF

of 0 (or 0%), where line pairs (a line pair is a sequence of one black line and one white line) can no longer be distinguished at all.

[000106]     The optical components described herein achieve high MTF performance due to the highly regular diffractive surfaces which produce the highly collimated output beams which are highly parallel to each other, exhibiting overall angular variation no greater (an potentially significantly less) than the angle subtended by an individual pixel from P (~$\Delta\beta$) e.g. exhibiting an overall angular variation of less than or equal to 0.5 milliradian, thus increasing the image quality of the final image as perceived by the wearer.

[000107]     The inventors have noticed a surprising effect that has arisen due to the increased performance of the optical components described herein. That is, a banding effect is observed in the final image by the wearer. Figure 10 illustrates the banding effect that is observed in the final image by the wearer. The intensity over observer's position in the eye box, rather that remaining substantially constant, varies almost from zero to maximum value due to the loop interference (described in more detail below). Therefore, depending on the position of the observer, the intensity varies heavily. The banding appears as vertical black and/or white stripes in the eye box. The dark and bright bands in the observed banding depend heavily on very small variations in the surface and grating line characteristics. Even some tens of nanometers changes in the surface level can create almost 100% changes in the local brightness.

[000108]     The inventors have identified that this observed banding effect is caused by different optical paths taken by incoherent light propagating through the fold zone 14 having equal (or very close to equal) path lengths.

[000109]     Figure 11 illustrates a portion of the diamond-like lattice of figure 9B to explain the cause of the banding effect. A beam that is guided onto point A otherwise referred to herein as a first splitting region of the fold SRG 54 is split into two versions of that beam. Both of these versions take respective optical paths between point A before being incident on the exit grating 16. The footprints of the two versions on the exit grating 16 substantially overlap. That is, the two versions are incident on the exit grating 16 at respective angles (having an angular variation less than or equal to 0.5 miliradian).

[000110]     Along a first optical path, a first version (of the two versions) propagates from point A (where beam 34(X) is first diffracted by the fold SRG 54) in beam 42a(X) by way of TIR to point B otherwise referred to herein as a second splitting region of the fold

SRG 54 (where beam 42a(X) is diffracted by the fold SRG 54) and propagates in first order reflection beam 40a(X) to a third splitting region of the fold SRG 54 by way of TIR.

[000111] Along a second optical path, a second version (of the two versions) propagates from point A in beam 34(X) by way of TIR to point C otherwise referred to herein as a fourth splitting region of the fold SRG 54 (where beam 34(X) is diffracted by the fold SRG 54) and propagates in beam 42b(X) to a fifth splitting region of the fold SRG 54 by way of TIR. The third and fifth splitting regions of the fold SRG 54 partially overlap which is shown collectively in Figure 11 as point D.

[000112] It has been observed by the inventors that banding occurs at very high MTF, which suggests that as the difference in path lengths between path A -> B -> D and path A -> C -> D is surprisingly very small (e.g. less than 50 nanometres) due to the highly regular diffractive surfaces of the fold zone 14, this causes destructive and constructive interference (referred to herein as loop interference) and thus dark and bright areas in the final image perceived by the wearer.

[000113] The inventors have recognised that, rather than attempting to eliminate the banding effect that is observed in the final image by the wearer, if the bands are shifted at a high enough rate spatially then the banding effect will not be perceivable by the wearer.

[000114] The inventors have observed that a phase change for the path A -> B -> D with respect to the path A -> C -> D will change the interference of the loop and thus shift the position of banding too.

[000115] In embodiments of the present disclosure, the phase change is made by a retarder film 1200 on the front surface of the optical component 10 in a position where there is TIR. Thus there is a birefringent (e.g. retardation) pattern on the front surface of the optical component 10 to create a phase change in the light. The term "retardation pattern" is used to refer to areas of the retarder film 1200 exhibiting different optical retardations.

[000116] As is known in the art, a retarder film is constructed such that when incident unpolarized light is incident on the film, one linear polarization state is delayed or "retarded" relative to an orthogonal linear polarization state. Light of the delayed polarization state is said to be polarized along an in-plane axis of the film. This is referred to as the "slow axis". Light of the other polarization state is said to be polarized along an orthogonal in-plane axis of the film. This is referred to the "fast axis".

[000117] In embodiments of the present disclosure, the polarization state of each beam interacting with the fold SRG 54 is controlled by the retarder film 1200.

[000118]     The polarization state of each beam interacting with one or more of (i) the incoupling SRG 52 and (ii) the exit SRG 56 may additionally be controlled by the retarder film 1200.

[000119]     The retarder film 1200 may cover the whole of the front surface of the optical component 10 (as shown in Figure 12) or one or more portions of the front surface of the optical component 10.

[000120]     The retardation pattern of the retarder film 1200 may be static (does not vary), i.e. the retardation is varied spatially so that path A -> B -> D has different phase change than path A -> C -> D.

[000121]     Alternatively, the retardation pattern of the retarder film 1200 may be modulated dynamically. This can be achieved for example with liquid crystal films or piezo electric thin films where the dynamic function is achieved by applying electric fields to the retarder film 1200 (the retardation pattern of the retarder film 1200 is electrically controllable).

[000122]     The direction of the fast axis of the birefringent material of the retarder film 1200 may be electrically controllable such that the direction of the fast axis can be varied in order to achieve the best modulation of the phase. Electrodes for controlling the retardation of the retarder film should be transparent, e.g. made from a transparent conducting film comprising a transparent conducting oxide such as indium tin oxide (ITO), fluorine doped tin oxide (FTO), and doped zinc oxide.

[000123]     The material of the retardation film 1200 may be a Faraday rotation material i.e. a material which exhibits the Faraday effect (which is well known in the art and therefore not described in detail herein), a Kerr medium material (the refractive index of the material changes in proportion to the square of an applied electric field), or an optically isotropic material comprising a zero order grating structure (whereby the groove spacing is less than half the wavelength of light, such that the only present order is the $m = 0$ order).

[000124]     Whilst embodiments using the retarder film 1200 have been described above with respect to the incoupling SRG 52, fold SRG 54, and exit SRG 56 all being on the rear surface of the optical component 10. As described above, the exit SRG 56 may be on the front surface of the optical component 10. In these embodiments, in addition to the retarder film 1200 on the front surface of the optical component 10 to control the polarization state of each beam interacting with the fold SRG 54 (which may additionally control the polarization state of each beam interacting with the incoupling SRG 52) a further retarder

film (having one or more of the properties of the retarder film 1200 described above) may be on the rear surface of the optical component 10 to control the polarization state of each beam interacting with the exit SRG 56.

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**[000125]**     In one aspect of the present disclosure there is provided a display system comprising: an optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating; and a light engine configured to generate multiple input beams, each beam being substantially collimated and directed to the incoupling grating in a unique inward direction, whereby the multiple input beams form a virtual image which depends on the location of that point in

10    the image; wherein the intermediate and exit grating have widths substantially larger than the beams' diameters; wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating; wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple

15    substantially parallel versions of that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating; wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form a version of the virtual

20    image; and wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of the optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface.

**[000126]**     The incoupling grating may be formed by modulations on the first surface of the optical waveguide and a polarization state of each beam interacting with the modulations

25    forming the incoupling grating on the first surface of the optical waveguide may be controlled by the retarder film.

**[000127]**     The exit grating may be formed by modulations on the first surface of the optical waveguide and a polarization state of each beam interacting with the modulations forming the exit grating on the first surface of the optical waveguide may be controlled by

30    the retarder film.

**[000128]**     The exit grating may be formed by modulations on the second surface of the optical waveguide and a polarization state of each beam interacting with the modulations

forming the exit grating on the second surface of the optical waveguide may be controlled by a further retarder film on the first surface of the optical waveguide.

[000129]     A retardation pattern of the retarder film may be static or dynamically variable.

[000130]     A direction of a fast axis of a birefringent material of the retarder film may be electrically controllable.

[000131]     The retarder film may be made of liquid crystals, a piezo electric material, a Faraday rotation material, a Kerr medium material, or an isotropic material comprising a zero order grating structure.

[000132]     The optical waveguide may be substantially flat so as to outwardly diffract the multiple versions of each beam substantially in parallel to one another and in an outward direction which substantially matches the unique inward direction in which that beam was incoupled. Alternatively, the optical waveguide is curved so as to form the version of the virtual image a finite distance from the waveguide

[000133]     The intermediate grating may have a height that increases in a direction along its width and away from the incoupling grating.

[000134]     The display system may be wearable by a user.

[000135]     The display system may be embodied in a wearable headpiece, the exit grating positioned forward of an eye of the user when worn to make the image visible to the user.

[000136]     The display system may comprise two such optical waveguides, each of which provides image light to a different eye of the user.

[000137]     In another aspect of the present disclosure there is provided an optical waveguide for a display system, the optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating, the incoupling grating arranged to receive multiple input beams, each beam being substantially collimated and directed to the incoupling grating in a unique inward direction whereby the multiple input beams form a virtual image; wherein the intermediate and exit grating have widths substantially larger than the beams' diameters; wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating; wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of

that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating; wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form a version of the virtual image; and wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of the optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface.

[000138]     In another aspect of the present disclosure there is provided a wearable headset comprising: a headpiece; an optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating; and a light engine mounted to the headpiece, the light engine configured to generate multiple input beams, each beam being substantially collimated and directed to the incoupling grating in a unique inward direction, whereby the multiple input beams form a virtual image which depends on the location of that point in the image; wherein the intermediate and exit grating have widths substantially larger than the beams' diameters; wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating; wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating; wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form a version of the virtual image; and wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of the optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface.

[000139]     The incoupling grating may be formed by modulations on the first surface of the optical waveguide and a polarization state of each beam interacting with the modulations forming the incoupling grating on the first surface of the optical waveguide may be controlled by the retarder film.

[000140]     The exit grating may be formed by modulations on the first surface of the optical waveguide and a polarization state of each beam interacting with the modulations forming the exit grating on the first surface of the optical waveguide may be controlled by the retarder film.

[000141]     The exit grating may be formed by modulations on the second surface of the optical waveguide and a polarization state of each beam interacting with the modulations forming the exit grating on the second surface of the optical waveguide may be controlled by a further retarder film on the first surface of the optical waveguide.

[000142]     A retardation pattern of the retarder film may be static or dynamically variable.

[000143]     A direction of a fast axis of a birefringent material of the retarder film may be electrically controllable.

[000144]     The retarder film may be made of liquid crystals, a piezo electric material, a Faraday rotation material, a Kerr medium material, or an isotropic material comprising a zero order grating structure.

[000145]     Although the subject matter has been described in language specific to structural features and/or methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above.  Rather, the specific features and acts described above are disclosed as example forms of implementing the claims.

Claims

1.      A display system comprising:

an optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating; and

a light engine configured to generate multiple input beams, each beam being substantially collimated and directed to the incoupling grating in a unique inward direction, whereby the multiple input beams form a virtual image which depends on the location of that point in the image;

wherein the intermediate and exit grating have widths substantially larger than the beams' diameters;

wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating;

wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating;

wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form  a version of the virtual image; and

wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of the optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface, and a retardation pattern of the retarder film is dynamically variable.


2.      A display system according to claim 1, wherein the incoupling grating is formed by modulations on the first surface of the optical waveguide and a polarization state of each beam interacting with the modulations forming the incoupling grating on the first surface of the optical waveguide is controlled by the retarder film.


3.      A display system according to claim 1, wherein the exit grating is formed by modulations on the first surface of the optical waveguide and a polarization state of each beam interacting with the modulations forming the exit grating on the first surface of the optical waveguide is controlled by the retarder film.

4.      A display system according to claim 1, wherein the exit grating is formed by modulations on the second surface of the optical waveguide and a polarization state of each beam interacting with the modulations forming the exit grating on the second surface of the optical waveguide is controlled by a further retarder film on the first surface of the optical waveguide.

5.      A display system according to claim 1, wherein a direction of a fast axis of a birefringent material of the retarder film is electrically controllable.

6.      A display system according to claim 1, wherein the retarder film is made of liquid crystals, a piezo electric material, a Faraday rotation material, a Kerr medium material, or an isotropic material comprising a zero order grating structure.

7.      A display system according to claim 1, wherein the optical waveguide is substantially flat so as to outwardly diffract the multiple versions of each beam substantially in parallel to one another and in an outward direction which substantially matches the unique inward direction in which that beam was incoupled.

8.      A display system according to claim 1, wherein the optical waveguide is curved so as to form the version of the virtual image a finite distance from the waveguide.

9.      A display system according to claim 1, wherein the intermediate grating has a height that increases in a direction along its width and away from the incoupling grating.

10.     A display system according to claim 1, which is wearable by a user.

11.     A display system according to claim 10, embodied in a wearable headpiece, the exit grating positioned forward of an eye of the user when worn to make the image visible to the user.

12.     An optical waveguide for a display system, the optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating, the incoupling grating arranged to receive multiple input beams, each beam being substantially collimated and directed to the incoupling grating

in a unique inward direction whereby the multiple input beams form a virtual image;

wherein the intermediate and exit grating have widths substantially larger than the beams' diameters;

wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating;

wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating;

wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form a version of the virtual image; and

wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of the optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface, and a retardation pattern of the retarder film is dynamically variable.
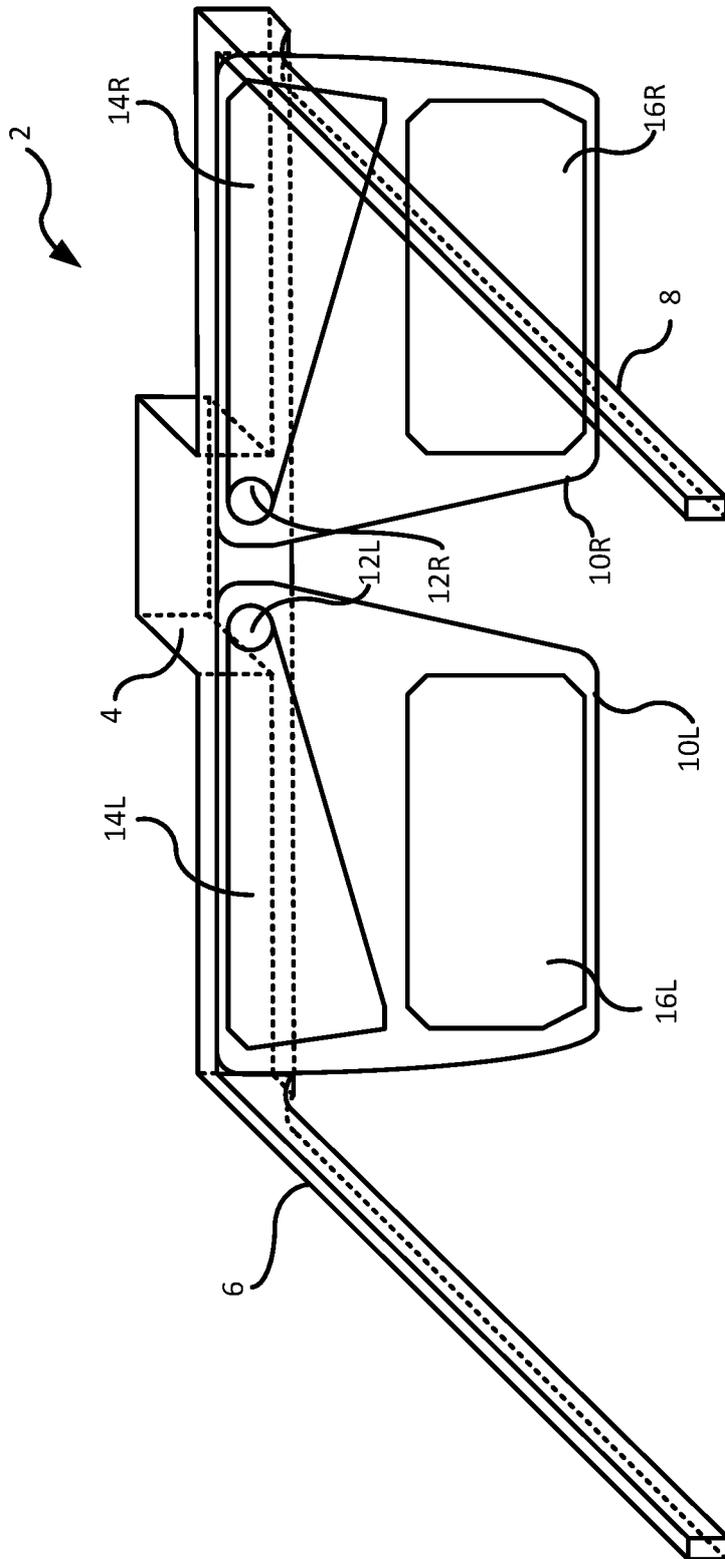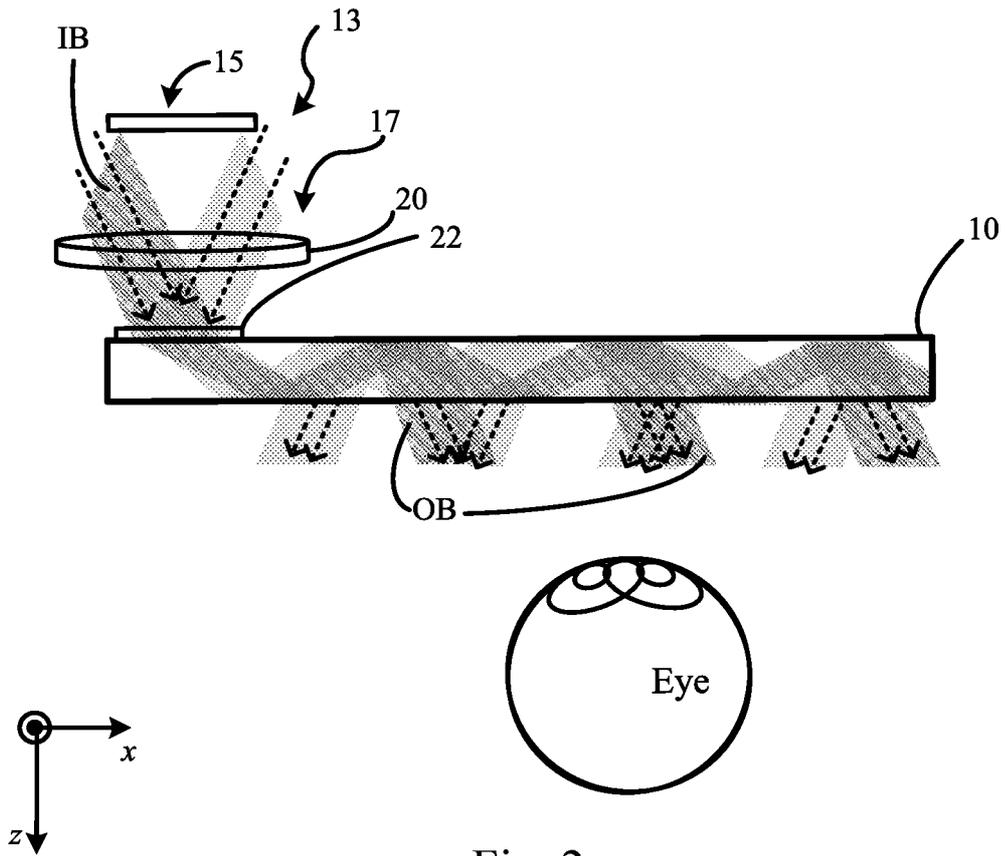
13.     An optical waveguide according to claim 12, wherein the optical waveguide is substantially flat so as to outwardly diffract the multiple versions of each beam substantially in parallel to one another and in an outward direction which substantially matches the unique inward direction in which that beam was incoupled.

14.     An optical waveguide according to claim 12, wherein the optical waveguide is curved so as to form the version of the virtual image a finite distance from the waveguide.

15.     A wearable headset comprising:

a headpiece;

an optical waveguide having an incoupling grating, an intermediate grating formed by modulations on a first surface of the optical waveguide, and an exit grating; and

a light engine mounted to the headpiece, the light engine configured to generate multiple input beams, each beam being substantially collimated and directed to the incoupling grating in a unique inward direction, whereby the multiple input beams form a virtual image which depends on the location of that point in the image;

wherein the intermediate and exit grating have widths substantially larger than the beams' diameters;

wherein the incoupling grating is arranged to couple each beam into the intermediate grating, in which that beam is guided onto multiple splitting regions of the intermediate grating in a direction along the width of the intermediate grating;

wherein the intermediate grating is arranged to split that beam at the splitting regions to provide multiple substantially parallel versions of that beam which are coupled into the exit grating, in which the multiple versions are guided onto multiple exit regions of the exit grating, the exit regions lying in a direction along the width of the exit grating;

wherein the exit grating is arranged to diffract the multiple versions of that beam outwardly, the multiple input beams thus causing multiple exit beams to exit the waveguide which form  a version of the virtual image; and

wherein a polarization state of each beam interacting with the modulations forming the intermediate grating on the first surface of the optical waveguide is controlled by a retarder film on a second surface of the optical waveguide opposing the first surface, and a retardation pattern of the retarder film is dynamically variable.

Fig. 1

Fig. 2
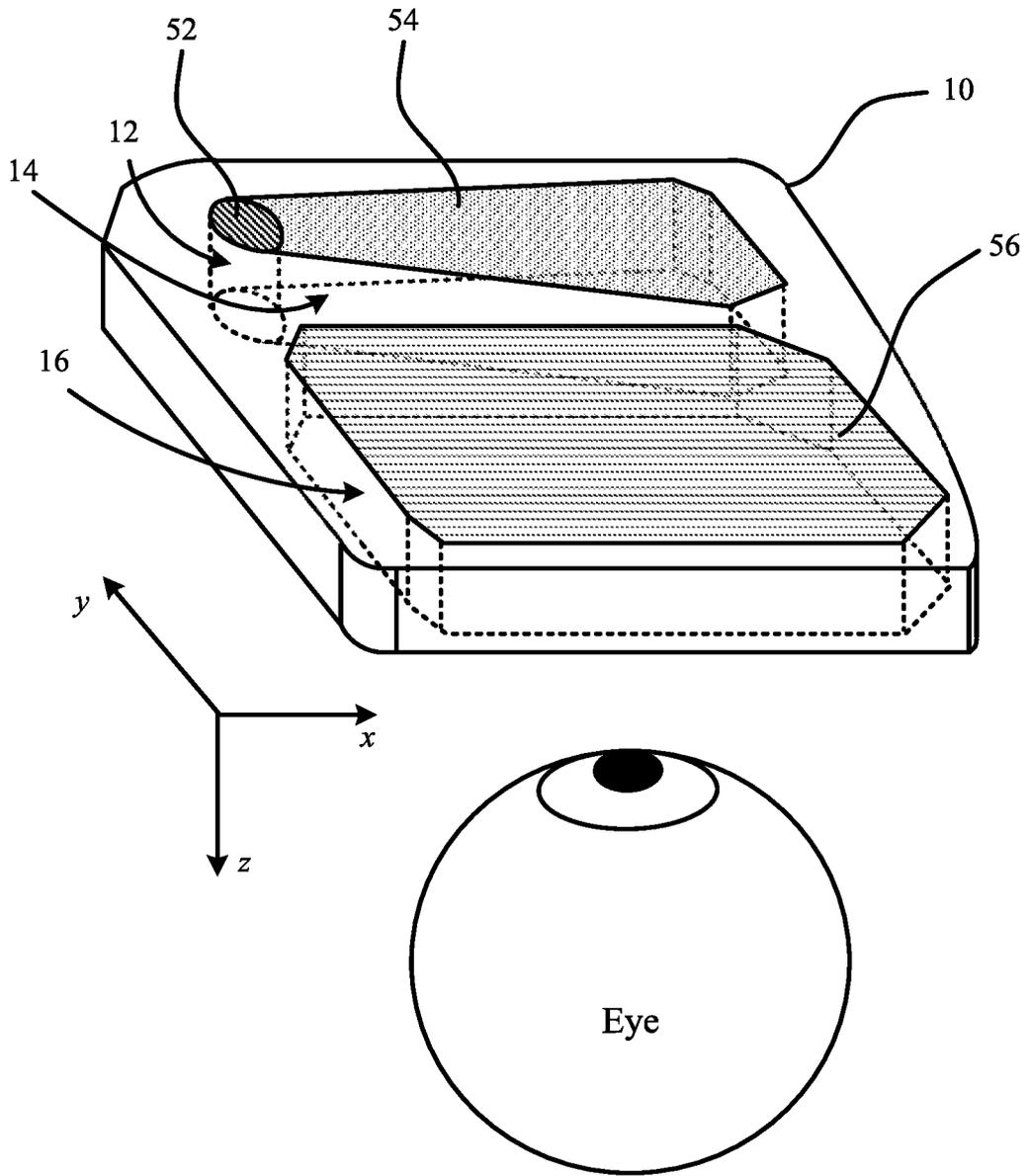
Fig. 3A
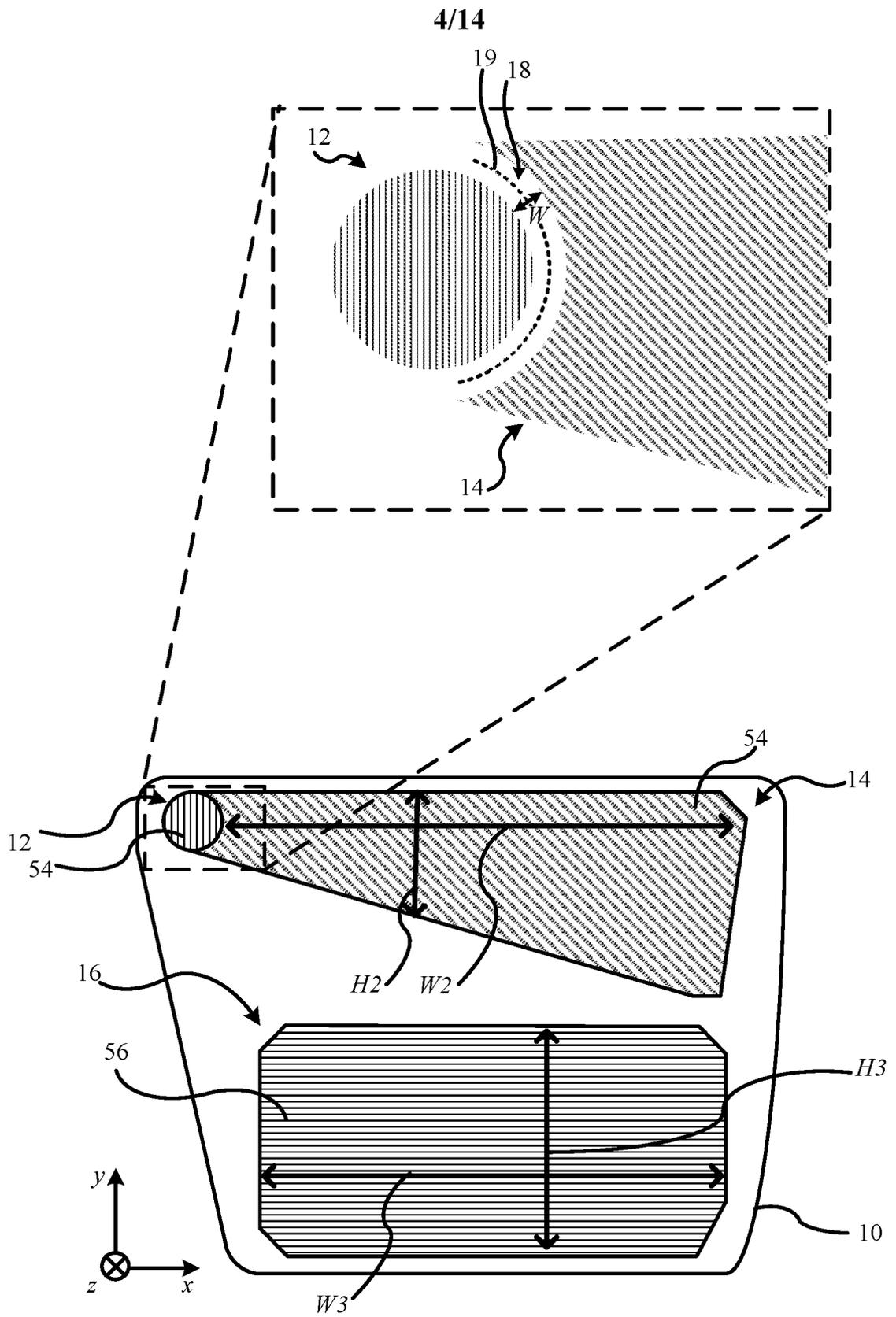
Fig. 3B
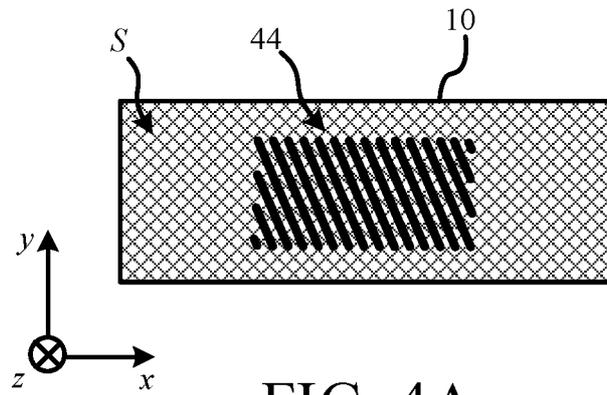
FIG. 4A
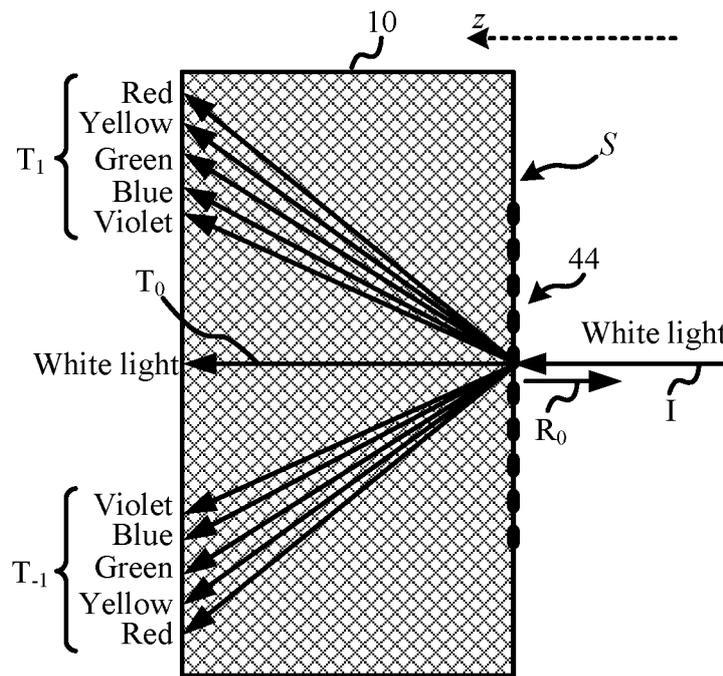


FIG. 4B
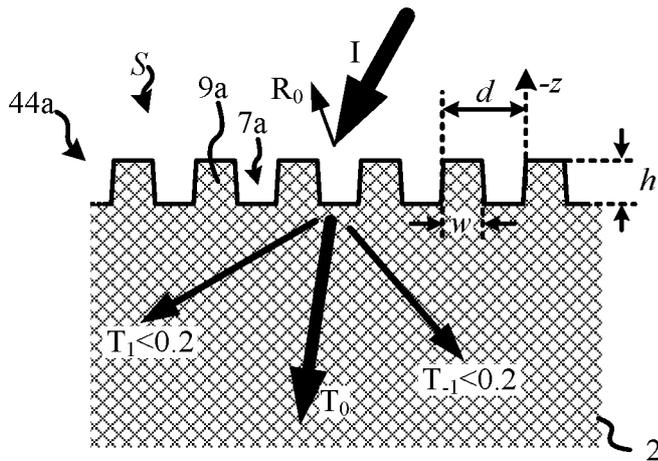
FIG. 5A
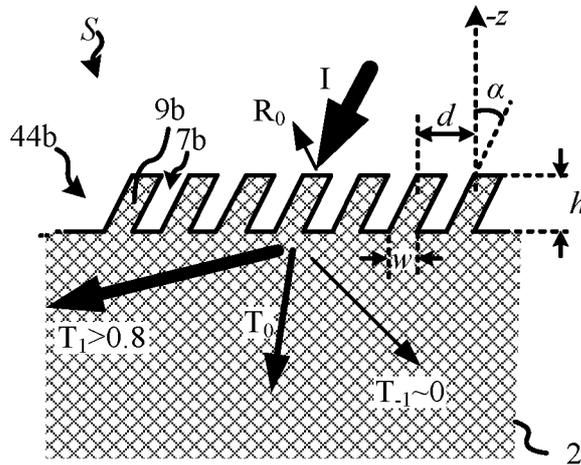


FIG. 5B
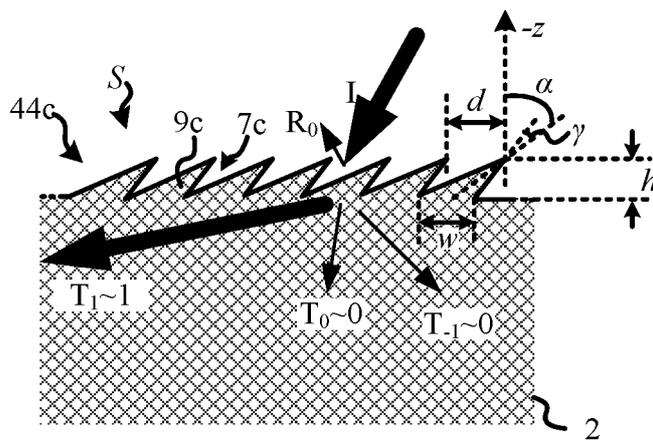


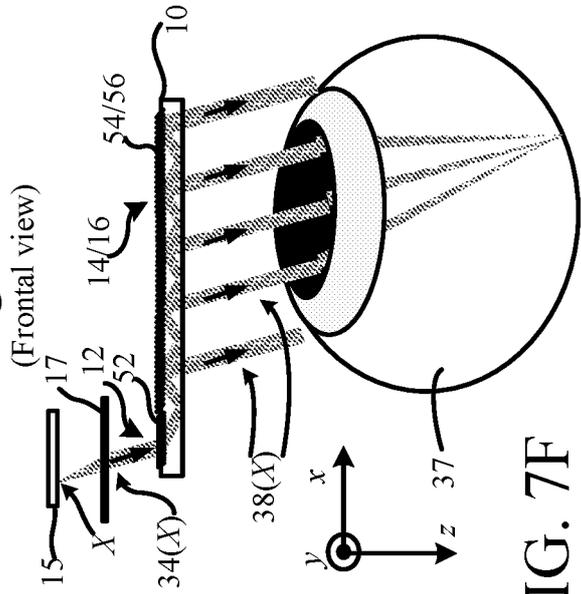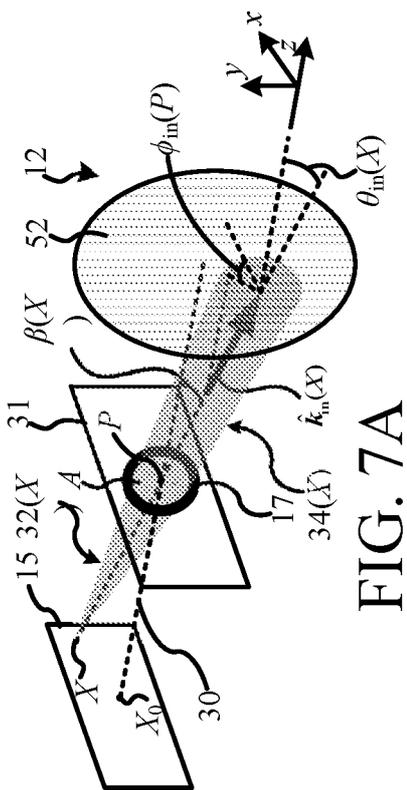FIG. 5C
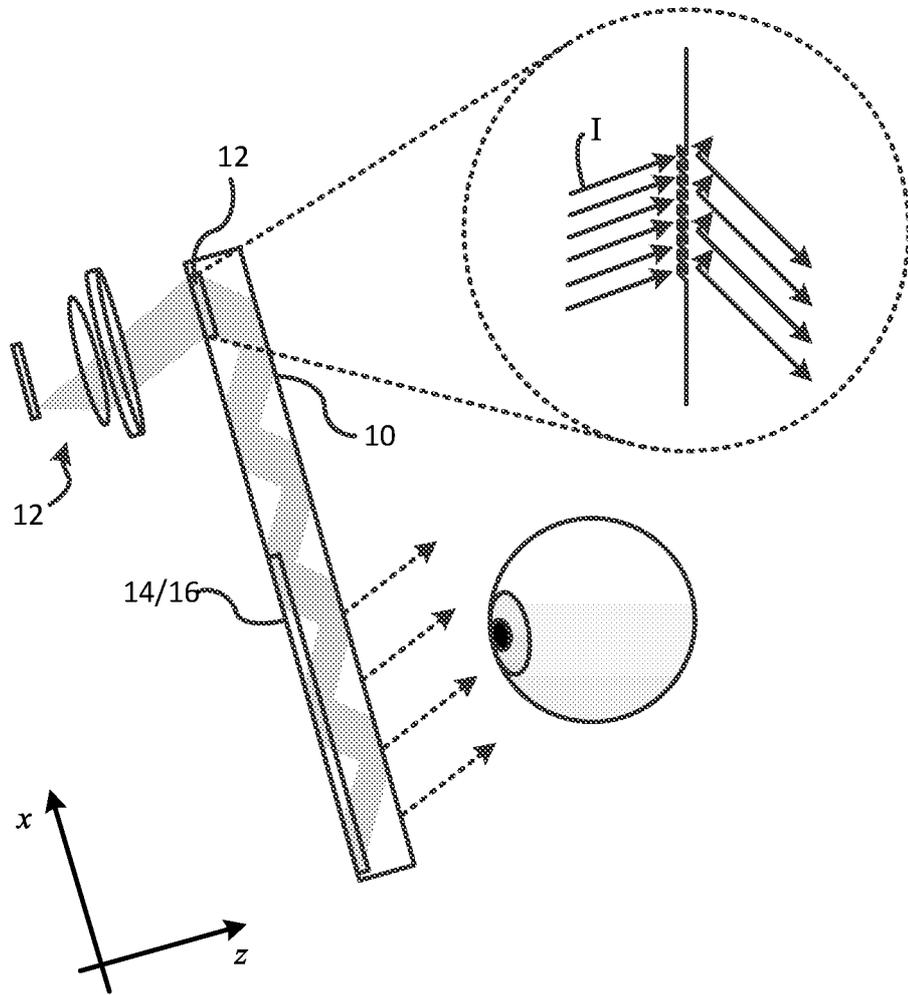
Fig. 6
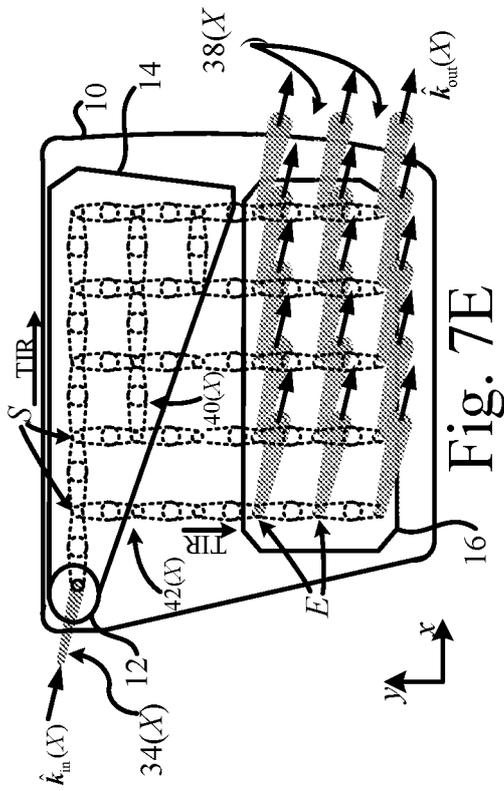
Fig. 7E
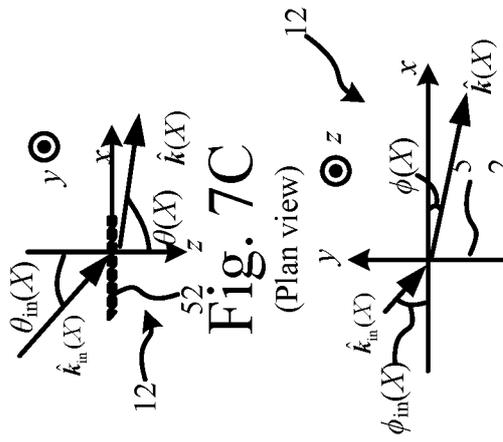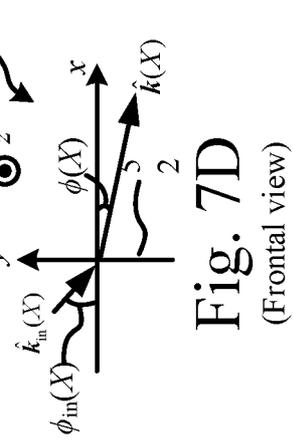(Frontal view)

FIG. 7F
(Plan view)

FIG. 7A
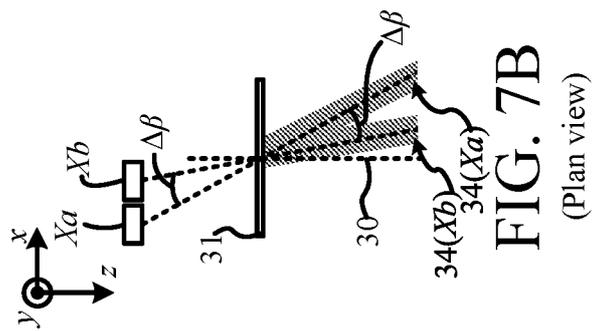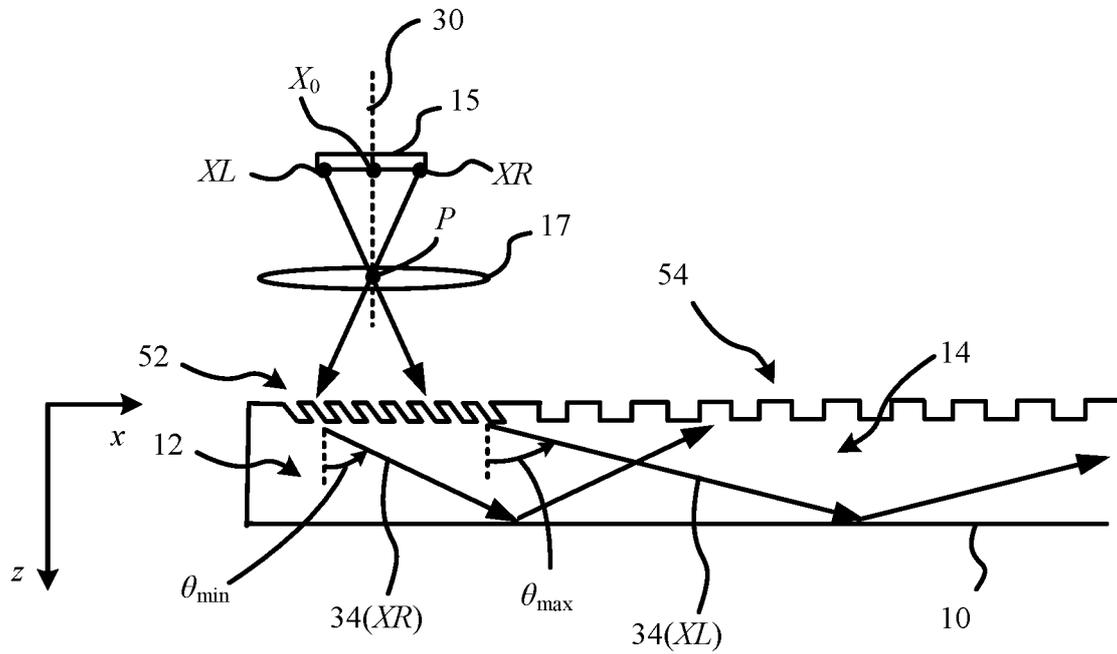
Fig. 7C
(Plan view)

Fig. 7D
(Frontal view)

FIG. 7B
(Plan view)

FIG. 7G

FIG. 8A

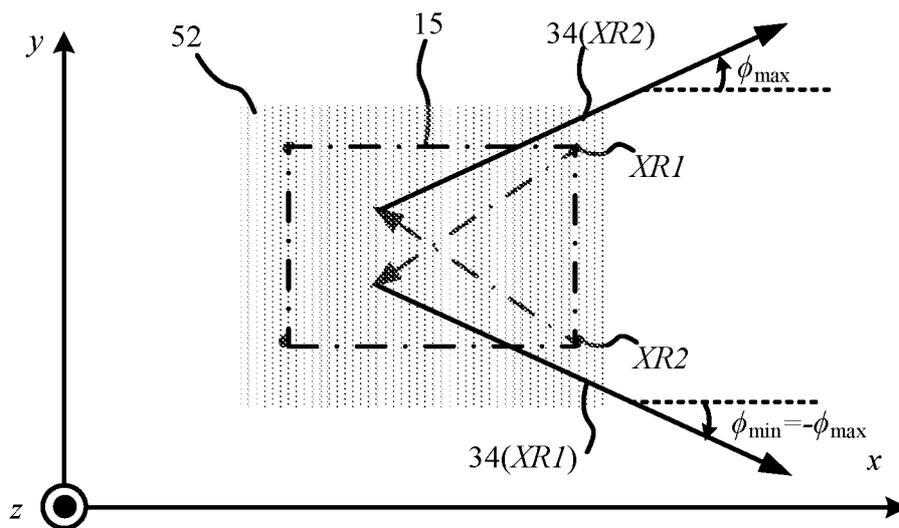(Plan view)



FIG. 8B

(Frontal view)
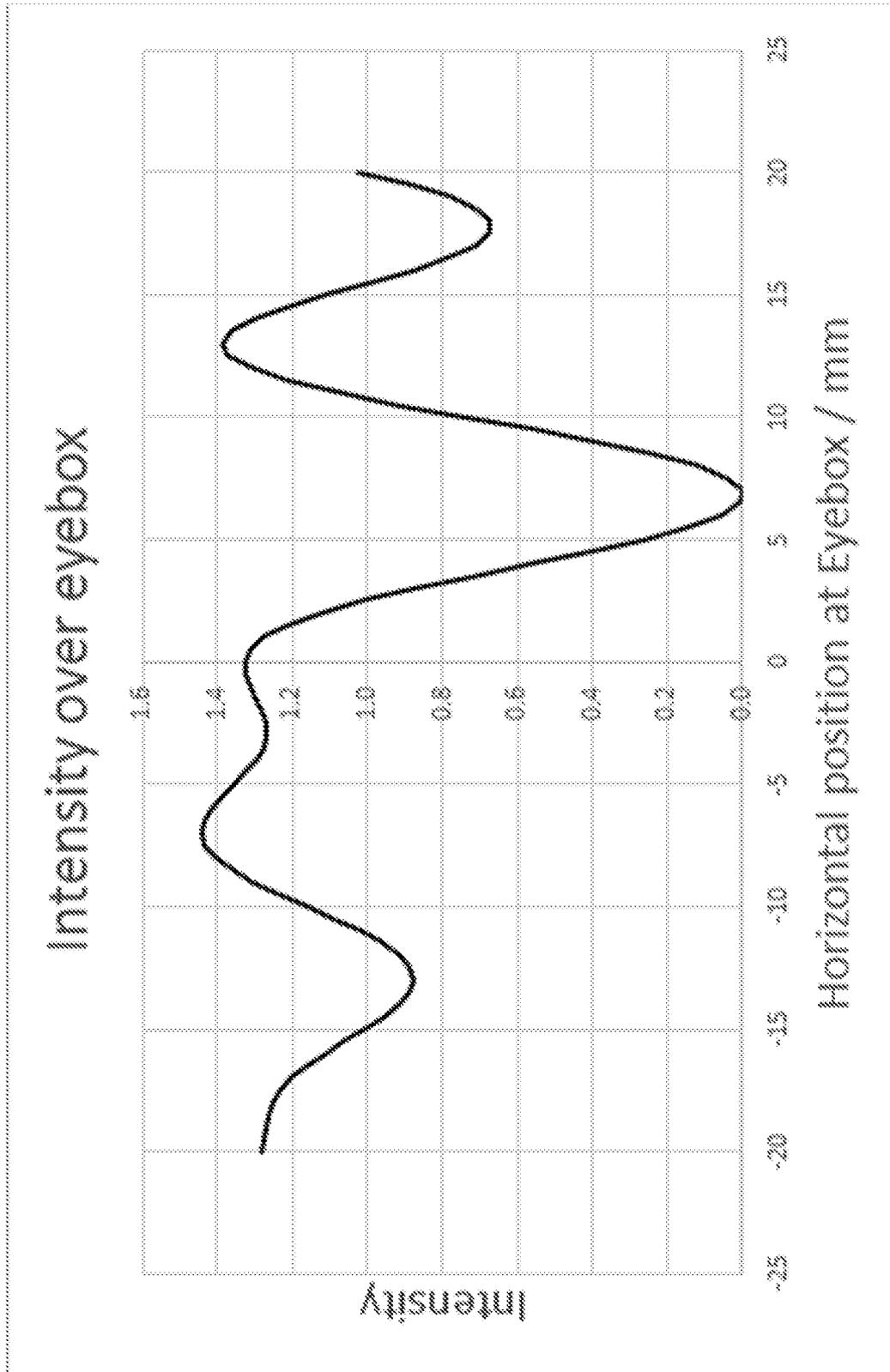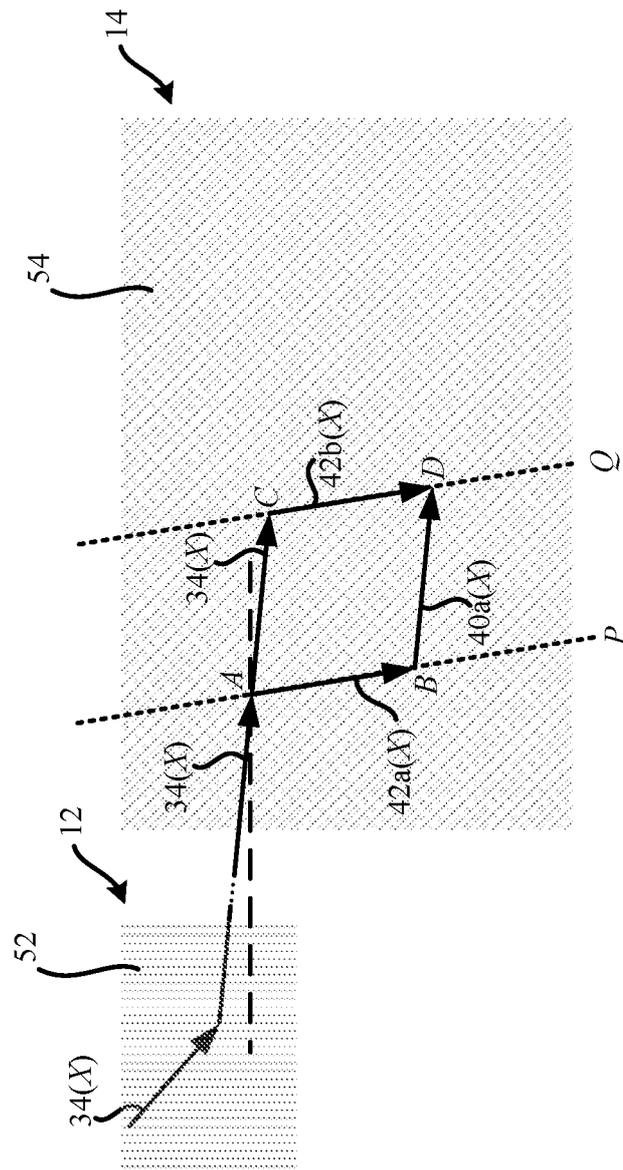
Fig. 9A



Fig. 9B

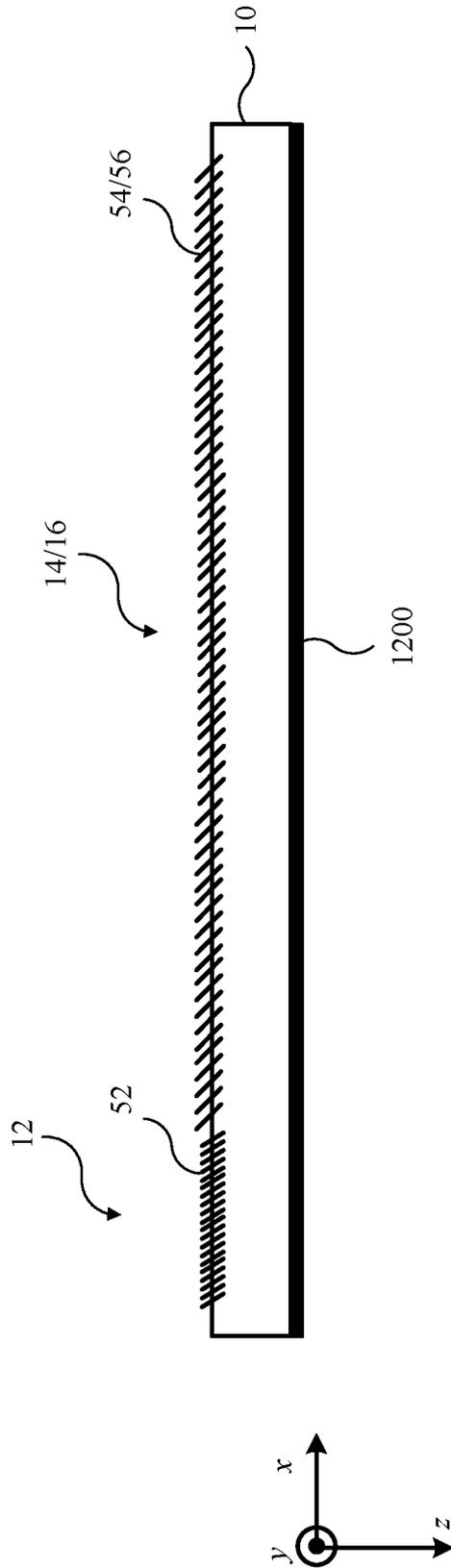(Frontal view)

Fig. 10

Fig. 11

Fig. 12

# INTERNATIONAL SEARCH REPORT

International application No

PCT/US2016/015869

## A. CLASSIFICATION OF SUBJECT MATTER

INV. G02B27/00 G02F1/01 G02B5/30 G02B27/01
ADD.

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

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02B G02F

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

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

EPO-Internal , WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | WO 2013/033274 AI (VUZIX CORP [US] ; TRAVERS PAUL J [US] ; SCHULTZ ROBERT J [US] ) 7 March 2013 (2013-03-07) paragraphs [0025] - [0036] , [0075] - [0080] ; figures 1,2,4 ----- | 1-15 |
| A | WO 2010/092409 AI ( LIGHT BLUE OPTICS LTD [GB] ; LACOSTE LILIAN [GB] ; CORBETT ALEXANDER DAV) 19 August 2010 (2010-08-19) page 18 - page 19, line 2; figures 3,6b, 6c, 9a, 9b page 21, paragraph 3 - page 22, paragraph 2 ----- | 1-15 |
| A | WO 2006/064334 AI (NOKIA CORP [FI] ; NOKIA INC [US] ; LEVOLA TAPANI [FI] ) 22 June 2006 (2006-06-22) page 17, line 25 - page 18, line 3; figures 6,8-10 ----- | 1-15 |

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

☒ See patent family annex.

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

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

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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 28 April 2016 | 12/05/2016 |

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

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# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2016/015869

| Patent document cited in search report | | Publication date | Patent family member(s) | | Publication date |
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