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PLANAR WAVEGUIDE APPARATUS WITH DIFFRACTION ELEMENT(S) AND SYSTEM EMPLOYING SAME

BACKGROUND

Technical Field

The present disclosure generally relates to optical devices and systems, for example projectors which project images or imagers that acquire images, for example for use with three-dimensional (3D) and /or four-dimensional (4D) light fields.

Description of the Related Art

A light field encompasses all the light rays at every point in space traveling in every direction. Light fields are considered four dimensional because every point in a three-dimensional space also has an associated direction, which is the fourth dimension.

Wearable three-dimensional displays may include a substrate guided optical device, also known as the light-guide optical element (LOE) system. Such devices are manufactured by, for example Lumus Ltd. However, these LOE system only projects a single depth plane, focused at infinity, with a spherical wave front curvature of zero.

One prior art system (Lumus) comprises multiple angle-dependent reflectors embedded in a waveguide to outcouple light from the face of the waveguide. Another prior art system (BAE) embeds a linear diffraction grating within the waveguide to change the angle of incident light propagating along the waveguide. By changing the angle of light beyond the threshold of TIR, the light escapes from one or more lateral faces of the waveguide. The linear diffraction grating has a low diffraction efficiency, so only a fraction of the light energy is directed out of the waveguide, each time the light encounters the linear diffraction grating. By outcoupling the light at multiple locations along the grating, the exit pupil of the display system is effectively increased.

A primary limitation of the prior art systems is that they only relay collimated images to the eyes (i.e., images at optical infinity). Collimated displays are adequate for many applications in avionics, where pilots are frequently focused upon very distant objects (e.g., distant terrain or other aircraft). However, for many other head-up or augmented reality applications, it is desirable to allow users to focus their eyes upon (i.e., "accommodate" to) objects closer than optical infinity.

BRIEF SUMMARY

Light that is coupled into a planar waveguide (*e.g.*, pane of glass, pane of fused silica, pane of polycarbonate), will propagate along the waveguide by total internal reflection (TIR). Planar waveguides may also be referred to as "substrate-guided optical elements," or "light guides."

If that light encounters one or more diffraction optical elements (DOE) in or adjacent to the planar waveguide, the characteristics of that light (e.g., angle of incidence, wavefront shape, wavelength, etc.) can be altered such that a portion of the light escapes TIR and emerges from one or more faces of the waveguide.

If the light coupled into the planar waveguide is varied spatially and/or temporally to contain or encode image data, that image data can propagate along the planar waveguide by TIR. Examples of elements that spatially vary light include LCDs, LCoS panels, OLEDs, DLPs, and other image arrays. Typically, these spatial light modulators may update image data for different cells or sub-elements at different points in time, and thus may produce sub-frame temporal variation, in addition to changing image data on a frame-by-frame basis to produce moving video. Examples of elements that temporally vary light include acousto-optical modulators, interferometric modulators, optical choppers, and directly modulated emissive light sources such as LEDs and laser diodes. These temporally varying elements may be coupled to one or more elements to vary the light spatially, such as scanning optical fibers, scanning mirrors, scanning prisms, and scanning cantilevers with reflective elements—or these temporally varying elements may be actuated directly to move them through space. Such scanning systems may utilize one or more scanned beams of light that are modulated over time and scanned across space to display image data.

If image data contained in spatially and/or temporally varying light that propagates along a planar waveguide by TIR encounters one or more DOEs in or adjacent to the planar waveguide, the characteristics of that light can be altered such that the image data encoded in light will escape TIR and emerge from one or more faces of the planar waveguide. Inclusion of one or more DOEs which combine a linear diffraction grating function or phase pattern with a radially symmetric or circular lens function or phase pattern, may advantageously allow steering of beams emanating from the face of the planar waveguide and control over focus or focal depth.

By incorporating such a planar waveguide system into a display system, the waveguide apparatus (e.g., planar waveguide and associated DOE) can be used to present images to one or more eyes. Where the planar waveguide is constructed of a partially or wholly transparent material, a human may view real physical objects through the waveguide. The waveguide display system can, thus, comprise an optically see-through mixed reality (or “augmented reality”) display system, in which artificial or remote image data can be superimposed, overlaid, or juxtaposed with real scenes.

The structures and approaches described herein may advantageously prodoce a relatively large eye box, readily accomodating viewer’s eye movements.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example, the shapes of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

Figure 1 is a schematic diagram showing an optical system including a waveguide apparatus, a subsystem to couple light to or from the waveguide apparatus, and a control subsystem, according to one illustrated embodiment.

Figure 2 an elevational view showing a waveguide apparatus including a planar waveguide and at least one diffractive optical element positioned within the planar waveguide, illustrating a number of optical paths including totally internally reflective optical paths and optical paths between an exterior and an interior of the planar waveguide, according to one illustrated embodiment.

Figure 3A a schematic diagram showing a linear diffraction or diffractive phase function, according to one illustrated embodiment.

Figure 3B a schematic diagram showing a radially circular lens phase function, according to one illustrated embodiment.

Figure 3C a schematic diagram showing a linear diffraction or diffractive phase function of a diffractive optical element that combines the linear diffraction and the radially circular lens phase functions, the diffractive optical element associated with a planar waveguide.

Figure 4A an elevational view showing a waveguide apparatus including a planar waveguide and at least one diffractive optical element carried on an outer surface of the planar waveguide, according to one illustrated embodiment.

Figure 4B an elevational view showing a waveguide apparatus including a planar waveguide and at least one diffractive optical element positioned internally immediately adjacent an outer surface of the planar waveguide, according to one illustrated embodiment.

Figure 4C an elevational view showing a waveguide apparatus including a planar waveguide and at least one diffractive optical element formed in an outer surface of the planar waveguide, according to one illustrated embodiment.

Figure 5A is a schematic diagram showing an optical system including a waveguide apparatus, an optical coupler subsystem to optically couple light to or from the waveguide apparatus, and a control subsystem, according to one illustrated embodiment.

Figure 5B is a schematic diagram of the optical system of Figure 5A illustrating generation of a single focus plane that is capable of being positioned closer than optical infinity, according to one illustrated embodiment.

Figure 5C is a schematic diagram of the optical system of Figure 5A illustrating generation of a multi-focal volumetric display, image or light field, according to one illustrated embodiment.

Figure 6 is a schematic diagram showing an optical system including a waveguide apparatus, an optical coupler subsystem including a plurality of projectors to optically couple light to a primary planar waveguide, according to one illustrated embodiment.

Figure 7 is an elevational view of a planar waveguide apparatus including a planar waveguide with a plurality of DOEs, according to one illustrated embodiment.

Figure 8 is an elevational view showing a portion of an optical system including a plurality of planar waveguide apparati in a stacked array, configuration or arrangement, according to one illustrated embodiment.

Figure 9 is a top plan view showing a portion of the optical system of Figure 8, illustrating a lateral shifting and change in focal distance in an image of a virtual object, according to one illustrated embodiment.

Figure 10 is an elevational view showing a portion of an optical system including a planar waveguide apparatus with a return planar waveguide, according to one illustrated embodiment.

Figure 11 is an elevational view showing a portion of an optical system including a planar waveguide apparatus with at least partially reflective mirrors or reflectors at opposed ends thereof to return light through a planar waveguide, according to one illustrated embodiment.

Figure 12 is a contour plot of a function for an exemplary diffractive element pattern, according to one illustrated embodiment.

Figures 13A-13E illustrate a relationship between a substrate index and a field of view, according to one illustrated embodiment.

DETAILED DESCRIPTION

In the following description, certain specific details are set forth in order to provide a thorough understanding of various disclosed embodiments. However, one skilled in the relevant art will recognize that embodiments may be practiced without one or more of these specific details, or with other methods, components, materials, etc. In other instances, well-known structures associated with computer systems, server computers, and/or communications networks have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the embodiments.

Unless the context requires otherwise, throughout the specification and claims which follow, the word “comprise” and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is as "including, but not limited to."

Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the content clearly dictates otherwise. It should also be noted that the term "or" is generally employed in its sense including "and/or" unless the content clearly dictates otherwise.

Numerous implementations are shown and described. To facilitate understanding, identical or similar structures are identified with the same reference numbers between the various drawings, even though in some instances these structures may not be identical.

The headings and Abstract of the Disclosure provided herein are for convenience only and do not interpret the scope or meaning of the embodiments.

In contrast to the conventional approaches, at least some of the devices and/or systems described herein enable: (1) a waveguide-based display that produces images at single optical viewing distance closer than infinity (e.g., arm's length); (2) a waveguide-based display that produces images at multiple, discrete optical viewing distances; and/or (3) a waveguide-based display that produces image layers stacked at multiple viewing distances to represent volumetric 3D objects. These layers in the light field may be stacked closely enough together to appear continuous to the human visual system (*i.e.*, one layer is within the cone of confusion of an adjacent layer). Additionally or alternatively, picture elements may be blended across two or more layers to increase perceived continuity of transition between layers in the light field, even if those layers are more sparsely stacked (*i.e.*, one layer is outside the cone of confusion of an adjacent layer). The display system may be monocular or binocular.

Embodiments of the described volumetric 3D displays may advantageously allow digital content superimposed over the user's view of the real world to be placed at appropriate viewing distances that do not require the user to draw his or her focus away from relevant real world objects. For example, a digital label or "call-out" for a real object can be placed at the same viewing distance as that object, so both label and object are in clear focus at the same time.

Embodiments of the described volumetric 3D displays may advantageously result in stereoscopic volumetric 3D displays that mitigate or entirely resolve the accommodation-vergence conflict produced in the human visual system by conventional stereoscopic displays. A binocular stereoscopic embodiment can produce 3D volumetric scenes in which the optical viewing distance (i.e., the focal distance) matches the fixation distance created by the stereoscopic imagery—*i.e.*, the stimulation to ocular vergence and ocular accommodation are matching, allowing users to point their eyes and focus their eyes at the same distance.

Figure 1 showing an optical system 100 including a primary waveguide apparatus 102, an optical coupler subsystem 104, and a control subsystem 106, according to one illustrated embodiment.

The primary waveguide apparatus 102 includes one or more primary planar waveguides 1 (only one show in Figure 1), and one or more diffractive optical elements (DOEs) 2 associated with each of at least some of the primary planar waveguides 1.

As best illustrated in Figure 2, the primary planar waveguides 1 each have at least a first end 108a and a second end 108b, the second end 108b opposed to the first end 108a along a length 110 of the primary planar waveguide

1. The primary planar waveguides 1 each have a first face 112a and a second face 112b, at least the first and the second faces 112a, 112b (collectively 112) forming an at least partially internally reflective optical path (illustrated by arrow 114a and broken line arrow 114b, collectively 114) along at least a portion of the length 110 of the primary planar waveguide 1. The primary planar waveguide(s) 1 may take a variety of forms which provides for substantially total internal reflection (TIR) for light striking the faces 112 at less than a defined critical angle. The planar waveguides 1 may, for example, take the form of a pane or plane of glass, fused silica, acrylic, or polycarbonate.

The DOEs 4 (illustrated in Figures 1 and 2 by dash-dot double line) may take a large variety of forms which interrupt the TIR optical path 114, providing a plurality of optical paths (illustrated by arrows 116a and broken line arrows 116b, collectively 116) between an interior 118 and an exterior 120 of the planar waveguide 1 extending along at least a portion of the length 110 of the planar waveguide 1. As explained below in reference to Figures 3A-3C, the DOEs 4 may advantageously combine the phase functions of a linear diffraction grating with that of a circular or radial symmetric lens, allowing positioning of apparent objects and focus plane for apparent objects. Such may be achieve on a frame-by-frame, subframe-by-subframe, or even pixel-by-pixel basis.

With reference to Figure 1, the optical coupler subsystem 104 optically couples light to, or from, the waveguide apparatus 102. As illustrated in Figure 1, the optical coupler subsystem may include an optical element 5, for instance a reflective surface, mirror, dichroic mirror or prism to optically couple light to, or from, an edge 122 of the primary planar waveguide 1. The optical coupler subsystem 104 may additionally or alternatively include a collimination element 6 that colliminates light.

The control subsystem 106 includes one or more light sources 11 and drive electronics 12 that generate image data that is encoded in the form of light that is spatially and/or temporally varying. As noted above, a collimination element 6 may colliminate the light, and the collimated light optically s coupled into one or more primary planar waveguides 1 (only one illustrated in Figures 1 and 2).

As illustrated in Figure 2, the light propagates along the primary planar waveguide with at least some reflections or “bounces” resulting from the TIR propagation. It is noted that some implementations may employ one or more reflectors in the internal optical path, for instance thin-films, dielectric coatings, metalized coatings, etc., which may facilitate reflection. Light propagates along the length 110 of the waveguide 1 intersects with one or more DOEs 4 at various positions along the length 110. As explained below in reference to Figures 4A-4C, the DOE(s) 4 may be incorporated within the primary planar waveguide 1 or abutting or adjacent one or more of the faces 112 of the primary planar waveguide 1. The DOE(s) 4 accomplishes at least two functions. The DOE(s) 4 shift an angle of the light, causing a portion of the light to escape TIR, and emerge from the interior 118 to the exterior 120 via one or more faces 112 of the primary planar waveguide 1. The DOE(s) 4 focus the out-coupled light at one or more viewing distances. Thus, someone looking through a face 112a of the primary planar waveguide 1 can see digital imagery at one or more viewing distances.

Figure 3A shows a linear diffraction or diffractive phase function 300, according to one illustrated embodiment. The linear diffraction or diffractive function 300 may be that of a linear diffractive grating, for example a Bragg grating.

Figure 3B showings a radially circular or radially symmetric lens phase function 310, according to one illustrated embodiment.

Figure 3B shows a phase pattern 320 for at least one diffractive optical element that combines the linear diffraction and the radially circular lens functions 300, 310, according to one illustrated embodiment, at least one diffractive optical element associated with at least one planar waveguide. Notably, each band has a curved wavefront.

While Figures 1 and 2 show the DOE 2 positioned in the interior 118 of the primary planar waveguide 1, spaced from the faces 112, the DOE 2 may be positioned at other locations in other implementations, for example as illustrated in Figures 4A-4C.

Figure 4A shows a waveguide apparatus 102a including a primary planar waveguide 1 and at least one DOE 2 carried on an outer surface or face 112 of the primary planar waveguide 1, according to one illustrated embodiment. For example, the DOE 2 may be deposited on the outer surface or face 112 of the primary planar waveguide 1, for instance as a patterned metal layer.

Figure 4B shows a waveguide apparatus 102b including a primary planar waveguide 1 and at least one DOE 2 positioned internally immediately adjacent an outer surface or face 112 of the primary planar waveguide 1, according to one illustrated embodiment. For example, the DOE 2 may be formed in the interior 118 via selective or masked curing of material of the primary planar waveguide 1. Alternatively, the DOE 2 may be a distinct physical structure incorporated into the primary planar waveguide 1.

Figure 4C shows a waveguide apparatus 102c including a primary planar waveguide 1 and at least one DOE 2 formed in an outer surface of the primary planar waveguide 1, according to one illustrated embodiment. The DOE 2 may, for example be etched, patterned, or otherwise formed in the outer surface or face 112 of the primary planar waveguide 1, for instances as grooves. For example, the DOE 2 may take the form of linear or saw tooth ridges and valleys which may be spaced at one or more defined pitches (*i.e.*, space between individual elements or features extending along the length 110). The pitch may be a linear function or may be a non-linear function.

The primary planar waveguide 1 is preferably at least partially transparent. Such allows one or more viewers to view the physical objects (*i.e.*, the real world) on a far side of the primary planar waveguide 1 relative to a vantage of the viewer. This may advantageously allow viewers to view the real world through the waveguide and simultaneously view digital imagery that is relayed to the eye(s) by the waveguide.

In some implementations a plurality of waveguides systems may be incorporated into a near-to-eye display. For example, a plurality of waveguides systems may be incorporated into a head-worn, head-mounted, or helmet-mounted display—or other wearable display.

In some implementations, a plurality of waveguides systems may be incorporated into a head-up display (HUD), that is not worn (e.g., an automotive HUD, avionics HUD). In such implementations, multiple viewers may look at a shared waveguide system or resulting image field. Multiple viewers may, for example see or optically perceive a digital or virtual object from different viewing perspectives that match each viewer's respective locations relative to the waveguide system.

The optical system 100 is not limited to use of visible light, but may also employ light in other portions of the electromagnetic spectrum (*e.g.*, infrared, ultraviolet) and/or may employ electromagnetic radiation that is outside the band of "light" (*i.e.*, visible, UV, or IR), for example employing electromagnetic radiation or energy in the microwave or X-ray portions of the electromagnetic spectrum.

In some implementations, a scanning light display is used to couple light into a plurality of primary planar waveguides. The scanning light display can comprise a single light source that forms a single beam that is scanned over time to form an image. This scanned beam of light may be intensity-modulated to form pixels of different brightness levels. Alternatively, multiple light sources may be used to generate multiple beams of light, which are scanned either with a shared scanning element or with separate scanning elements to form imagery. These light sources may comprise different wavelengths, visible and/or non-visible, they may comprise different geometric points of origin (X, Y, or Z), they may enter the scanner(s) at different angles of incidence, and may create light that corresponds to different portions of one or more images (flat or volumetric, moving or static).

The light may, for example, be scanned to form an image with a vibrating optical fiber, for example as discussed in U.S. patent application Serial

No. 13/915,530, International Patent Application Serial No. PCT/US2013/045267, and U.S. provisional patent application Serial No. 61/658,355. The optical fiber may be scanned biaxially by a piezoelectric actuator. Alternatively, the optical fiber may be scanned uniaxially or triaxially. As a further alternative, one or more optically components (*e.g.*, rotating polygonal reflector or mirror, oscillating reflector or mirror) may be employed to scan an output of the optical fiber.

The optical system 100 is not limited to use in producing images or as an image projector or light field generation. For example, the optical system 100 or variations thereof may optical, be employed as an image capture device, such as a digital still or digital moving image capture or camera system.

Figure 5A shows an optical system 500 including a waveguide apparatus, an optical coupler subsystem to optically couple light to or from the waveguide apparatus, and a control subsystem, according to one illustrated embodiment.

Many of the structures of the optical system 500 of Figure 5A are similar or even identical to those of the optical system 100 of Figure 1. In the interest of conciseness, in many instances only significant differences are discussed below.

The optical system 500 may employ a distribution waveguide apparatus, to relay light along a first axis (vertical or Y-axis in view of Figure 5A), and expand the light's effective exit pupil along the first axis (*e.g.*, Y-axis). The distribution waveguide apparatus, may, for example include a distribution planar waveguide 3 and at least one DOE 4 (illustrated by double dash-dot line) associated with the distribution planar waveguide 3. The distribution planar waveguide 3 may be similar or identical in at least some respects to the primary planar waveguide 1, having a different orientation therefrom. Likewise, the at least one DOE 4 may be similar or identical in at least some respects to the DOE 2. For example, the distribution planar waveguide 3 and/or DOE 4 may be comprised of the same materials as the primary planar waveguide 1 and/or DOE 2, respectively

The relayed and exit-pupil expanded light is optically coupled from the distribution waveguide apparatus into one or more primary planar waveguide 1. The primary planar waveguide 1 relays light along a second axis, preferably orthogonal to first axis, (*e.g.*, horizontal or X-axis in view of Figure 5A). Notably, the second axis can be a non-orthogonal axis to the first axis. The primary planar waveguide 1 expands the light's effective exit pupil along that second axis (*e.g.* X-axis). For example, a distribution planar waveguide 3 can relay and expand light along the vertical or Y-axis, and pass that light to the primary planar waveguide 1 which relays and expands light along the horizontal or X-axis.

Figure 5B shows the optical system 500, illustrating generation thereby of a single focus plane that is capable of being positioned closer than optical infinity.

The optical system 500 may include one or more sources of red, green, and blue laser light 11, which may be optically coupled into a proximal end of a single mode optical fiber 9. A distal end of the optical fiber 9 may be threaded or received through a hollow tube 8 of piezoelectric material. The distal end protrudes from the tube 8 as fixed-free flexible cantilever 7. The piezoelectric tube 8 is associated with 4 quadrant electrodes (not illustrated). The electrodes may, for example, be plated on the outside, outer surface or outer periphery or diameter of the tube 8. A core electrode (not illustrated) is also located in a core, center, inner periphery or inner diameter of the tube 8.

Drive electronics 12, for example electrically coupled via wires 11, drive opposing pairs of electrodes to bend the piezoelectric tube 8 in two axes independently. The protruding distal tip of the optical fiber 7 has mechanical modes of resonance. The frequencies of resonance which depend upon a diameter, length, and material properties of the optical fiber 7. By vibrating the piezoelectric tube 8 near a first mode of mechanical resonance of the fiber cantilever 7, the fiber cantilever 7 is caused to vibrate, and can sweep through large deflections. By stimulating resonant vibration in two axes, the tip of the fiber cantilever 7 is scanned biaxially in an area filling 2D scan. By modulating an intensity of light source(s) 11 in synchrony with the scan of the fiber cantilever 7, light emerging from the fiber cantilever 7 forms an image. Descriptions of such a set up are provide in U.S. patent application Serial No. 13/915,530, International Patent Application Serial No. PCT/US2013/045267, and U.S. provisional patent application Serial No. 61/658,355, all of which are incorporated by reference herein in their entireties.

A component of an optical coupler subsystem 104 collimates the light emerging from the scanning fiber cantilever 7. The collimated light is reflected by mirrored surface 5 into a narrow distribution planar waveguide 3 which contains at least one diffractive optical element (DOE) 4. The collimated light propagates vertically (*i.e.*, relative to view of Figure 5B) along the distribution planar waveguide 3 by total internal reflection, and in doing so repeatedly intersects with the DOE 4. The DOE 4 preferably has a low diffraction efficiency. This causes a fraction (*e.g.*, 10%) of the light to be diffracted toward an edge of the larger primary planar waveguide 1 at each point of intersection with the DOE 4, and a fraction of the light to continue on its original trajectory down the length of the distribution planar waveguide 3 via TIR. At each point of intersection with the DOE 4, additional light is diffracted toward the entrance of the primary waveguide 1. By dividing the incoming light into multiple outcoupled sets, the exit pupil of the light is expanded vertically by the DOE 4 in the distribution planar waveguide 3. This vertically expanded light coupled out of distribution planar waveguide 3 enters the edge of the primary planar waveguide 1.

Light entering primary waveguide 1 propagates horizontally (*i.e.*, relative to view of Figure 5B) along the primary waveguide 1 via TIR. As the light intersects with DOE 2 at multiple points as it propagates horizontally along at least a portion of the length of the primary waveguide 1 via TIR. The DOE 2 may advantageously be designed or configured to have a phase profile that is a summation of a linear diffraction grating and a radially symmetric diffractive lens.

The DOE 2 may advantageously have a low diffraction efficiency. At each point of intersection between the propagating light and the DOE 2, a fraction of the light is diffracted toward the adjacent face of the primary waveguide 1 allowing the light to escape the TIR, and emerge from the face of the primary waveguide 1. The radially symmetric lens aspect of the DOE 2 additionally imparts a focus level to the diffracted light, both shaping the light wavefront (*e.g.*, imparting a curvature) of the individual beam as well as steering the beam at an angle that matches the designed focus level. Figure 5B illustrates four beams 18, 19, 20, 21 extending geometrically to a focus point 13, and each beam is advantageously imparted with a convex wavefront profile with a center of radius at focus point 13 to produce an image or virtual object 22 at a given focal plane.

Figure 5C shows the optical system 500 illustrating generation thereby of a multi-focal volumetric display, image or light field.

The optical system 500 may include one or more sources of red, green, and blue laser light 11, optically coupled into a proximal end of a single mode optical fiber 9. A distal end of the optical fiber 9 may be threaded or received through a hollow tube 8 of piezoelectric material. The distal end protrudes from the tube 8 as fixed-free flexible cantilever 7. The piezoelectric tube 8 is associated with 4 quadrant electrodes (not illustrated). The electrodes may, for example, be plated on the outside or outer surface or periphery of the tube 8. A core electrode (not illustrated) is positioned in a core, center, inner surface, inner periphery or inner diameter of the tube 8.

Drive electronics 12, for example coupled via wires 11, drive opposing pairs of electrodes to bend the piezoelectric tube 8 in two axes independently. The protruding distal tip of the optical fiber 7 has mechanical modes of resonance. The frequencies of resonance of which depend upon the a diameter, length, and material properties of the fiber cantilever 7. By vibrating the piezoelectric tube 8 near a first mode of mechanical resonance of the fiber cantilever 7, the fiber cantilever 7 is caused to vibrate, and can sweep through large deflections. By stimulating resonant vibration in two axes, the tip of the fiber cantilever 7 is scanned biaxially in an area filling 2D scan. By modulating the intensity of light source(s) 11 in synchrony with the scan of the fiber cantilever 7, the light emerging from the fiber cantilever 7 forms an image. Descriptions of such a set up are provide in U.S. patent application Serial No. 13/915,530, International Patent Application Serial No. PCT/US2013/045267, and U.S. provisional patent application Serial No. 61/658,355, all of which are incorporated by reference herein in their entireties.

A component of an optical coupler subsystem 104 collimates the light emerging from the scanning fiber cantilever 7. The collimated light is reflected by mirrored surface 5 into a narrow distribution planar waveguide 3, which contains diffractive optical element (DOE) 4. The collimated light propagates along the distribution planar waveguide by total internal reflection (TIR), and in doing so repeatedly intersects with the DOE 4. The DOE has a low diffraction efficiency. This causes a fraction (*e.g.*, 10%) of the light to be diffracted toward an edge of a larger primary planar waveguide 1 at each point of intersection with the DOE 4, and a fraction of the light to continue on its original trajectory down the distribution planar waveguide 3 via TIR. At each point of intersection with the DOE 4, additional light is diffracted toward the entrance of the primary planar waveguide 1. By dividing the incoming light into multiple out-coupled sets, the exit pupil of the light is expanded vertically by DOE 4 in distribution planar waveguide 3. This vertically expanded light coupled out of the distribution planar waveguide 3 enters the edge of the primary planar waveguide 1.

Light entering primary waveguide 1 propagates horizontally (*i.e.*, relative to view of Figure 5C) along the primary waveguide 1 via TIR. As the light intersects with DOE 2 at multiple points as it propagates horizontally along at least a portion of the length of the primary waveguide 1 via TIR. The DOE 2 may advantageously be designed or configured to have a phase profile that is a summation of a linear diffraction grating and a radially symmetric diffractive lens.

The DOE 2 may advantageously have a low diffraction efficiency. At each point of intersection between the propagating light and the DOE 2, a fraction of the light is diffracted toward the adjacent face of the primary waveguide 1 allowing the light to escape the TIR, and emerge from the face of the primary waveguide 1. The radially symmetric lens aspect of the DOE 2 additionally imparts a focus level to the diffracted light, both shaping the light wavefront (*e.g.*, imparting a curvature) of the individual beam as well as steering the beam at an angle that matches the designed focus level. Figure 5C illustrates a first set of four beams 18, 19, 20, 21 extending geometrically to a focus point 13, and each beam 18, 19, 20, 21 is advantageously imparted with a convex wavefront profile with a center of radius at focus point 13 to produce another portion of the image or virtual object 22 at a respective focal plane. Figure 5C illustrates a second set of four beams 24, 25, 26, 27 extending geometrically to a focus point 23, and each beam 24, 25, 26, 27 is advantageously imparted with a convex wavefront profile with a center of radius at focus point 23 to produce another portion of the image or virtual object 22 at a respective focal plane.

Figure 6 shows an optical system 600, according to one illustrated embodiment. The optical system 600 is similar in some respects to the optical systems 100, 500. In the interest of conciseness, only some of the difference are discussed.

The optical system 600 includes a waveguide apparatus 102, which as described above may comprise one or more primary planar waveguides 1 and associated DOE(s) 2 (not illustrated in Figure 6). In contrast to the optical system 500 of Figures 5A-5C, the optical system 600 employs a plurality of microdisplays or projectors 602a-602e (only five shown, collectively 602) to provide respective image data to the primary planar waveguide(s) 1. The microdisplays or projectors 602 are generally arrayed or arranged along are disposed along an edge 122 of the primary planar waveguide 1. There may, for example, be a one to one (1:1) ratio or correlation between the number of planar waveguides 1 and the number of microdisplays or projectors 602. The microdisplays or projectors 602 may take any of a variety of forms capable of providing images to the primary planar waveguide 1. For example, the microdisplays or projectors 602 may take the form of light scanners or other display elements, for instance the cantilevered fiber 7 previously described. The optical system 600 may additionally or alternatively include a collimination element 6 that colliminates light provided from microdisplay or projectors 602 prior to entering the primary planar waveguide(s) 1.

The optical system 600 can enable the use of a single primary planar waveguide 1, rather using two or more primary planar waveguides 1 (*e.g.*, arranged in a stacked configuration along the Z-axis of Figure 6). The multiple microdisplays or projectors 602 can be disposed, for example, in a linear array along the edge 122 of a primary planar waveguide that is closest to a temple of a viewer's head. Each microdisplay or projector 602 injects modulated light encoding sub-image data into the primary planar waveguide 1 from a different respective position, thus generating different pathways of light. These different pathways can cause the light to be coupled out of the primary planar waveguide 1 by a multiplicity of DOEs 2 at different angles, focus levels, and/or yielding different fill patterns at the exit pupil. Different fill patterns at the exit pupil can be beneficially used to create a light field display. Each layer in the stack or in a set of layers (*e.g.*, 3 layers) in the stack may be employed to generate a respective color (*e.g.*, red, blue, green). Thus, for example, a first set of three adjacent layers may be employed to respectively produce red, blue and green light at a first focal depth. A second set of three adjacent layers may be employed to respectively produce red, blue and green light at a second focal depth. Multiple sets may be employed to generate a full 3D or 4D color image field with various focal depths.

Figure 7 shows a planar waveguide apparatus 700 including a planar waveguide 1 with a plurality of DOEs 2a-2d (four illustrated, each as a double dash-dot line, collectively 2), according to one illustrated embodiment.

The DOEs 2 are stacked along an axis 702 that is generally parallel to the field-of-view of the planar waveguide 700. While illustrated as all being in the interior 118, in some implementations one, more or even all of the DOEs may be on an exterior of the planar waveguide 1.

In some implementations, each DOE 2 may be capable of being independently switched ON and OFF. That is each DOE 2 can be made active such that the respective DOE 2 diffracts a significant fraction of light that intersects with the respective DOE 2, or it can be rendered inactive such that the respective DOE 2 either does not diffract light intersecting with the respective DOE 2 at all, or only diffracts an insignificant fraction of light. "Significant" in this context means enough light to be perceived by the human visual system when coupled out of the planar waveguide 1, and "insignificant" means not enough light to be perceived by the human visual system, or a low enough level to be ignored by a viewer.

The switchable DOEs 2 may be switched on one at a time, such that only one DOE 2 in the primary planar waveguide 1 is actively diffracting the light in the primary planar waveguide 1, to emerge from one or more faces 112 of the primary planar waveguide 1 in a perceptible amount. Alternatively, two or more DOEs 2 may be switched ON simultaneously, such that their diffractive effects are combined.

The phase profile of each DOE 2 is advantageously a summation of a linear diffraction grating and a radially symmetric diffractive lens. Each DOE 2 preferably has a low (*e.g.*, less than 50%) diffraction efficiency.

The light intersects with the DOEs at multiple points along the length of the planar waveguide 1 as the light propagates horizontally in the planar waveguide 1 via TIR. At each point of intersection between the propagating light and a respective one of the DOEs 2, a fraction of the light is diffracted toward the adjacent face 112 of the planar waveguide 1, allowing the light to escape TIR and emerge from the face 112 of the planar waveguide 1.

The radially symmetric lens aspect of the DOE 2 additionally imparts a focus level to the diffracted light, both shaping the light wavefront (*e.g.*, imparting a curvature) of the individual beam, as well as steering the beam at an angle that matches the designed focus level. Such is best illustrated in Figure 5B where the four beams 18, 19, 20, 21, if geometrically extended from the far face 112b of the planar waveguide 1, intersect at a focus point 13, and are imparted with a convex wavefront profile with a center of radius at focus point 13.

Each DOE 2 in the set of DOEs can have a different phase map. For example, each DOE 2 can have a respective phase map such that each DOE 2, when switched ON, directs light to a different position in X, Y, or Z. The DOEs 2 may, for example, vary from one another in their linear grating aspect and/or their radially symmetric diffractive lens aspect. If the DOEs 2 vary from one another in their diffractive lens aspect, different DOEs 2 (or combinations of DOEs 2) will produce sub-images at different optical viewing distances—*i.e.*, different focus distances. If the DOEs 2 vary from one another in their linear grating aspect, different DOEs 2 will produce sub-images that are shifted laterally relative to one another. Such lateral shifts can be beneficially used to create a foveated display, to steer a display image with non-homogenous resolution or other non-homogenous display parameters (*e.g.*, luminance, peak wavelength, polarization, etc.) to different lateral positions, to increase the size of the scanned image, to produce a variation in the characteristics of the exit pupil, and/or to generate a light field display. Lateral shifts may be advantageously employed to preform tiling or realize a tiling effect in generated images.

For example, a first DOE 2 in the set, when switched ON, may produce an image at an optical viewing distance of 1 meter (*e.g.*, focal point 23 in Figure 5C) for a viewer looking into the primary or emission face 112a of the planar waveguide 1. A second DOE 2 in the set, when switched ON, may produce an image at an optical viewing distance of 1.25 meters (*e.g.*, focal point 13 in Figure 5C) for a viewer looking into the primary or emission face 112a of the planar waveguide 1. By switching exemplary DOEs 2 ON and OFF in rapid temporal sequence (*e.g.*, on a frame-by-frame basis, a sub-frame basis, a line-by-line basis, a sub-line basis, pixel-by-pixel basis, or sub-pixel-by-sub-pixel basis) and synchronously modulating the image data being injected into the planar waveguide 1, for instance by a scanning fiber display sub-system, a composite multi-focal volumetric image is formed that is perceived to a be a single scene to the viewer. By rendering different objects or portions of objects to sub-images relayed to the eye of the viewer (at location 22 in Figure 5C) by the different DOEs 2, virtual objects or images are placed at different optical viewing distances, or a virtual object or image can be represented as a 3D volume that extends through multiple planes of focus.

Figure 8 shows a portion of an optical system 800 including a plurality of planar waveguide apparati 802a-802d (four shown, collectively 802), according to one illustrated embodiment.

The planar waveguide apparati 802 are stacked, arrayed, or arranged along an axis 804 that is generally parallel to the field-of-view of the portion of the optical system 800. Each of the planar waveguide apparati 802 includes at least one planar waveguide 1 (only one called out in Figure 8) and at least one associated DOE 2 (illustrated by dash-dot double line, only one called out in Figure 8). While illustrated as all being in the interior 118, in some implementations one, more or even all of the DOEs 2 may be on an exterior of the planar waveguide 1. Additionally or alternatively, while illustrated with a single linear array of DOEs 2 per planar waveguide 1, one or more of the planar waveguides 1 may include two or more stacked, arrayed or arranged DOEs 2, similar to the implementation described with respect to Figure 7.

Each of the planar waveguide apparati 802a-802d may function analogously to the operation of the DOEs 2 of the optical system 7 (Figure 7), That is the DOEs 2 of the respective planar waveguide apparati 802 may each have a respective phase map, the phase maps of the various DOEs 2 being different from one another. While dynamic switching (*e.g.*, ON/OFF) of the DOEs 2 was employed in the optical system 700 (Figure 7), such can be avoided in the optical system 800. Instead of, or in additional to dynamic switching, the optical system 800 may selectively route light to the planar waveguide apparati 802a-802d based on the respective phase maps. Thus, rather than turning ON a specific DOE 2 having a desired phase map, the optical system 800 may route light to a specific planar waveguide 802 that has or is associated with a DOE 2 with the desired phase mapping. Again, the may be in lieu of, or in addition to, dynamic switching of the DOEs 2.

In one example, the microdisplays or projectors may be selectively operated to selectively route light to the planar waveguide apparati 802a-802d based on the respective phase maps. In another example, each DOE 4 may be capable of being independently switched ON and OFF, similar to as explained with reference to switching DOEs 2 ON and OFF. The DOEs 4 may be switche dON and OFF to selectively route light to the planar waveguide apparati 802a-802d based on the respective phase maps.

Figure 8 also illustrated outward emanating rays from two of the planar waveguide apparati 802a, 802d. For sake of illustration, a first one of the planar waveguide apparatus 802a produces a plane or flat wavefront (illustrated by flat lines 804 about rays 806, only one instance of each called out for sake of drawing clarity) at an infinite focal distance. In contrast, another one of the planar waveguide apparatus 802d produces a convex wavefront (illustrated by arc 808 about rays 810, only one instance of each called out for sake of drawing clarity) at a defined focal distance less than infinite (*e.g.*, 1 meter).

As illustrated in Figure 9, the planar waveguide apparati 802a-802d may laterally shift the appearance and/or optical viewing distances—*i.e.*, different focus distances of a virtual object 900a-900c with respect to an exit pupil 902.

Figure 10 shows a portion of an optical system 1000 including a planar waveguide apparatus 102 with a return planar waveguide 1002, according to one illustrated embodiment.

The planar waveguide apparatus 102 may be similar to those described herein, for example including one or more planar waveguides 1 and one or more associated DOEs 2.

In contrast to previously described implementations, the optical system 1000 includes the return planar waveguide 1002, which provides a TIR optical path for light to return from one end 108b of the planar waveguide 1 to the other end 108a of the planar waveguide 1 for recirculation. The optical system 1000 also include is a first mirror or reflector 1004, located at a distal end 108a (*i.e.*, end opposed to end at which light first enters). The mirror or reflector 1004 at the distal end 108a may be completely reflecting. The optical system 1000 optionally includes is a second mirror or reflector 1006, located at a proximate end 108b (*i.e.*, end at which light first enters as indicated by arrow 1010). The second mirror or reflector 1006 may be a dichroic mirror or prism, allowing light to initially enter the optical system, and then reflecting light returned from the distal end 108a.

Thus, light may enter at the proximate end 108b as indicated by arrow 1010. The light may traverse or propagate along the planar waveguide 1 in a first pass, as illustrated by arrow 1012, exiting at the distal end 112b. The first mirror or reflector 1004 may reflect the light to propagate via the return planar waveguide 1002, as illustrated by arrow 1014. The second mirror or reflector 1006 may reflect the remaining light back to the planar waveguide 1 for a second pass, as illustrated by arrow 1016. This may repeat until there is no appreciable light left to recirculate. This recirculation of light may advantageously increase luminosity or reduce system luminosity requirements.

Figure 11 shows a portion of an optical system 1100 including a planar waveguide apparatus 102 with at least partially reflective mirrors or reflectors 1102a, 1102b at opposed ends 112a, 112b thereof to return light through a planar waveguide 1, according to one illustrated embodiment.

Light may enter at the proximate end 108b as indicated by arrow 1110. The light may traverse or propagate along the planar waveguide 1 in a first pass, as illustrated by arrow 1112, exiting at the distal end 112b. The first mirror or reflector 1102a may reflect the light to propagate the planar waveguide 1, as illustrated by arrow 1114. The second mirror or reflector 1006 may optionally reflect the remaining light back to the planar waveguide 1 for a second pass (not illustrated). This may repeat until there is no appreciable light left to recirculate. This recirculation of light may advantageously increase luminosity or reduce system luminosity requirements.

In some implementations, an optical coupling system collimates the light emerging from a multiplicity of displays or projectors, prior to optically coupling the light to a planar waveguide. This optical coupling system may include, but is not limited to, a multiplicity of DOEs, refractive lenses, curved mirrors, and/or freeform optical elements. The optical coupling subsystem may serve multiple purposes, such as collimating the light from the multiplicity of displays and coupling the light into a waveguide. The optical coupling subsystem may include a mirrored surface or prism to reflect or deflect the collimated light into a planar waveguide.

In some implementations the collimated light propagates along a narrow planar waveguide via TIR, and in doing so repeatedly intersects with a multiplicity of DOEs 2. As described above, the DOEs 2 may comprise or implement respective different phase maps, such that the DOEs 2 steer the light in the waveguide along respective different paths. For example, if the multiple DOEs 2 contain linear grating elements with different pitches, the light is steered at different angles, which may beneficially be used to create a foveated display, steer a non-homogenous display laterally, increase the lateral dimensions of the out-coupled image, increase effective display resolution by interlacing, generate different fill patterns at the exit pupil, and/or generate a light field display.

As previously described, a multiplicity of DOEs 2 may be arrayed or arranged or configured in a stack within or on a respective planar waveguide 1, 3.

The DOEs 2 in the distribution planar waveguide 3 may have a low diffraction efficiency, causing a fraction of the light to be diffracted toward the edge of the larger primary planar waveguide 1, at each point of intersection, and a fraction of the light to continue on its original trajectory down the distribution planar waveguide 3 via TIR. At each point of intersection, additional light is diffracted toward an edge or entrance of the primary planar waveguide 1. By dividing the incoming light into multiple out-coupled sets, the exit pupil of the light is expanded vertically by multiplicity of DOEs 4 in distribution planar waveguide 3.

As described above, vertically expanded light coupled out of the distribution planar waveguide 3 enters an edge of larger primary planar waveguide 1, and propagates horizontally along the length of the primary planar waveguide 1 via TIR. The multiplicity of DOEs 4 in the narrow distribution planar waveguide 3 can have a low diffraction efficiency, causing a fraction of the light to be diffracted toward the edge of the larger primary planar waveguide 1 at each point of intersection, and a fraction of the light to continue on its original trajectory down the distribution planar waveguide 3 by TIR. At each point of intersection, additional light is diffracted toward the entrance of larger primary planar waveguide 1. By dividing the incoming light into multiple out-coupled sets, the exit pupil of the light is expanded vertically by the multiplicity of DOEs 4 in distribution planar waveguide 3. A low diffraction efficiency in the multiplicity of DOEs in the primary planar waveguide 1 enables viewers to see through the primary planar waveguide 1 to view real objects, with a minimum of attenuation or distortion.

In at least one implementation, the diffraction efficiency of the multiplicity of DOEs 2 is low enough to ensure that any distortion of real world is not perceptible to a human looking through the waveguide at the real world.

Since a portion or percentage of light is diverted from the internal optical path as the light transits the length of the planar waveguide(s) 1, 3, less light may be diverted from one end to the other end of the planar waveguide 1, 3 if the diffraction efficiency is constant along the length of the planar waveguide 1,3. This change or variation in luminosity or output across the planar waveguide 1, 3 is typically undesirable. The diffraction efficiency may be varied along the length to accommodate for this undesired optical effect. The diffraction efficiency may be varied in a fixed fashion, for example by fixedly varying a pitch of the DOEs 2, 4 along the length when the DOEs 2, 4 and/or planar waveguide 1, 3 is manufactured or formed. Intensity of light output may be advantageously be increased or varied as a function of lateral offest of pixels in the display or image.

Alternatively, the diffraction efficiency may be varied dynamically, for example by fixedly varying a pitch of the DOEs 2, 4 along the length when the DOEs 2, 4 and/or planar waveguide 1,3 is in use. Such may employ a variety of techniques, for instance varying an electrical potential or voltage applied to a material (*e.g.*, liquid crystal). For example, voltage changes could be applied, for instance via electrodes, to liquid crystals dispersed in a polymer host or carrier medium. The voltage may be used to change the molecular orientation of the liquid crystals to either match or not match a refractive index of the host or carrier medium. As explained herein, a structure which employs a stack or layered array of switchable layers (*e.g.*, DOEs 2, planer waveguides 1), each independently controlable may be employed to advantageous affect.

In at least one implementation, the summed diffraction efficiency of a subset of simultaneously switched on DOEs 2 of the multiplicity of DOEs 2 is low enough to enable viewers to see through the waveguide to view real objects, with a minimum of attenuation or distortion.

It may be preferred if the summed diffraction efficiency of a subset of simultaneously switched on DOEs 2 of the multiplicity of DOEs 2 is low enough to ensure that any distortion of real world is not perceptible to a human looking through the waveguide at the real world.

As described above, each DOE 2 in the multiplicity or set of DOEs 2 may be capable of being switched ON and OFF—i.e., it can be made active such that the respective DOE 2 diffracts a significant fraction of light that intersects with the respective DOE 2, or can be rendered inactive such that the respective DOE 2 either does not diffract light intersecting with it at all, or only diffracts an insignificant fraction of light. “Significant” in this context means enough light to be perceived by the human visual system when coupled out of the waveguide, and “insignificant” means not enough light to be perceived by the human visual system, or a low enough level to be ignored by a viewer.

The switchable multiplicity of DOEs 2 may be switched ON one at a time, such that only one DOE 2 associated with the large primary planar waveguide 1 is actively diffracting the light in the primary planar waveguide 1 to emerge from one or more faces 112 of the primary planar waveguide 1 in a perceptible amount. Alternatively, two or more DOEs 2 in the multiplicity of DOEs 2 may be switched ON simultaneously, such that their diffractive effects are advantageously combined. It may thus be possible to realize 2^N combinations, where N is the number of DOEs 2 in associated with a respective planar waveguide 1, 3.

In at least some implementations, the phase profile or map of each DOE 2 in at least the large or primary planar waveguide 1 is or reflects a summation of a linear diffraction grating and a radially symmetric diffractive lens, and has a low (less than 50%) diffraction efficiency. Such is illustrated in Figures 3A-3C. In particular, the hologram phase function comprises a linear function substantially responsible for coupling the light out of the waveguide, and a lens function substantially responsible for creating a virtual image

p(x, y) = p1(x, y) + p2(x, y),

where

$$p1(x,y) = \frac{x0y1y}{nr},$$

and

$$p2(x,y) = x2y0(\frac{x}{\mathrm{nr}})^2 + x2y2(\frac{x}{\mathrm{nr}})^2(\frac{y}{\mathrm{nr}})^2 + x2y4(\frac{x}{\mathrm{nr}})^2(\frac{y}{\mathrm{nr}})^4 + x4y0(\frac{x}{\mathrm{nr}})^4 + x4y2(\frac{x}{\mathrm{nr}})^4(\frac{y}{\mathrm{nr}})^2 + x6y0(\frac{x}{\mathrm{nr}})^6 + x0y2(\frac{y}{\mathrm{nr}})^2 + x0y4(\frac{y}{\mathrm{nr}})^4 + x0y6(\frac{y}{\mathrm{nr}})^6$$

In this example, the coefficients of p2 are constrained to produce a radially symmetric phase function.

An example EDGE element was designed for a 40 degree diagonal field of view having a 16 x 9 aspect ratio. The virtual object distance is 500 mm (2 diopters). The design wavelength is 532 nanometers. The substrate material is fused silica, and the y angles of incidence in the substrate lie between 45 and 72 degrees. The y angle of incidence required to generate an on axis object at is 56 degrees. The phase function defining the example element is:

$$\Phi g = \frac{12.4113x^2}{mm^2} - \frac{0.00419117x^4}{mm^4} - \frac{14315.y}{mm} - \frac{12.4113y^2}{mm^2} - \frac{0.00838233x^2y^2}{mm^4} - \frac{0.00419117y^4}{mm^4}$$

The diffractive element pattern is generated by evaluating the 2 pi phase contours. Figure 12 shows a contour plot illustrating the function evaluated over a 20 x 14 mm element area (required to provide a 4 mm eye box at a 25 mm eye relief. The contour interval was chosen to make the groove pattern visible. The actual groove spacing in this design is approximately 0.5 microns.

The relationship between substrate index and field of view is described in Figures 13A-13E. The relationship is non-trivial, but a higher substrate index always allows for a large field of view. One should always prefer higher index of refraction materials if all other considerations are equal.

First order diffraction efficiencies should be in the neighborhood of 0.01 to 0.20. Lower values require higher input energy to create specified image brightness, while larger values lead to increased pupil non-uniformity. The particular value chosen depends on the particular application requirements.

It may be advantageous to vary one or more characteristics of the DOEs 2, for example along a longitudinal or axial dimension thereof. For instance, a pitch may be varied, or a height of a groove or angle (*e.g.*, 90 degree, 60 degree) of a structure forming the DOE 2 or portion thereof. Such may advantageously address higher order aberrations.

Two beams of mutually coherent light may be employed to dynamically vary the properties of the DOEs 2. The beams of mutually coherent light may, for example, be generated via a single laser and a beam splitter. The beams may interact with a liquid crystal film to create a high interference pattern on or in the liquid crystal film to dynamcially generate at least one diffraction element, *e.g.*, a grating such as a Bragg grating. The DOEs 2 may be addressable on a pixel-by-pixel basis. Thus, for example, a pitch of the elements of the DOEs 2 may be varied dynamically. The interference patterns are typically temporary, but may be held sufficiently long to affect the diffraction of light.

Further, diffraction gratings may be employed to split lateral chromatic aberrations. For example, a relative difference in angle can be expect for light of different colors when passed through a DOE 2. Where a pixel is being generated via three different colors, the colors may not be preceived as being in the same positions due to the difference in bending of the respective colors of light. This may be addressed by introducing a very slight delay between the signals used to generate each color for any given pixel. One way of addressing this is via software, where image data is "pre-misaligned "or pre-wrapped, to accommodate the differences in location of the various colors making up each respective pixel. Thus, the image data for generating a blue component of a pixel in the image may be offset spatially and/or temporally with respect to a red component of the pixel to accomdate a known or expected shift due to diffraction. Likewise, a green component may be offset spatially and/or temporally with respect to a red and blue components of the pixel.

The image field may be generated to have a higer concentration of light or image information proximal to the viewer in contrast to portions that are relatively distal to the viewer. Such may advantageously take into account the typially higher sensitivity of the vision system for relative close objects or images as compared to more distal objects of images. Thus, virtual objects in the foreground of an image field may be rendered at a higher resolution (*e.g.*, higher density of focal planes) than objects in the background of the image field. The various structures and approaches described herein advantageously allow such non-uniform operation and generation of the image field.

In at least some implementations, the light intersects with the multiplicity of DOEs 2 at multiple points as it propagates horizontally via TIR. At each point of intersection between the propagating light and the multiplicity of DOEs 2, a fraction of the light is diffracted toward the adjacent face of the planar waveguide 1, 3 allowing the light to escape TIR and emerge from the face 112 of the planar waveguide1, 3.

In at least some implementations, the radially symmetric lens aspect of the DOE 2 additionally imparts a focus level to the diffracted light, both shaping the light wavefront (*e.g.*, imparting a curvature) of the individual beam as well as steering the beam at an angle that matches the designed focus level. In Figure 5B, the four beams 18, 19, 20, 21, if geometrically extended from the far face of the primary planar waveguide 1, intersect at a focus point 13, and are imparted with a convex wavefront profile with a center of radius at focus point 13.

In at least some implementations, each DOE 2 in the multiplicity or set of DOEs 2 can have a different phase map, such that each DOE 2, when switched ON or when fed light, directs light to a different position in X, Y, or Z. The DOEs 2 may vary from one another in their linear grating aspect and/or their radially symmetric diffractive lens aspect. If the DOEs 2 vary in their diffractive lens aspect, different DOEs 2 (or combinations of DOEs) will produce sub-images at different optical viewing distances—*i.e.*, different focus distances. If the DOEs 2 vary in their linear grating aspect, different DOEs 2 will produce sub-images that are shifted laterally relative to one another.

In at least some implementations, lateral shifts generated by the multiplicity of DOEs can be beneficially used to create a foveated display. In at least some implementations, lateral shifts generated by the multiplicity of DOEs 2 can be beneficially used to steer a display image with non-homogenous resolution or other non-homogenous display parameters (*e.g.*, luminance, peak wavelength, polarization, etc.) to different lateral positions. In at least some implementations, lateral shifts generated by the multiplicity of DOEs can be beneficially used to increase the size of the scanned image. In at least some implementations, lateral shifts generated by the multiplicity of DOEs can be beneficially used to produce a variation in the characteristics of the exit pupil. In at least some implementations, lateral shifts generated by the multiplicity of DOEs can be beneficially used, to produce a variation in the characteristics of the exit pupil and generate a light field display.

In at least some implementations, a first DOE 2, when switched ON, may produce an image at a first optical viewing distance 23 (Figure 5C) for a viewer looking into the face of the primary planar waveguide 1. A second DOE 2 in the multiplicity, when switched ON, may produce an image at a second optical viewing distance 13 (Figure 5C) for a viewer looking into the face of the waveguide.

In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence. In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence on a frame-by-frame basis. In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence on a sub-frame basis. In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence on a line-by-line basis. In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence on a sub-line basis. In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence on a pixel-by-pixel basis. In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence on a sub-pixel-by-sub-pixel basis. In at least some implementations, DOEs 2 are switched ON and OFF in rapid temporal sequence on some combination of a frame-by-frame basis, a sub-frame basis, a line-by-line basis, a sub-line basis, pixel-by-pixel basis, and/or sub-pixel-by-sub-pixel basis.

In at least some implementations, while DOEs 2 are switched ON and OFF the image data being injected into the waveguide by the multiplicity of microdisplays is simultaneously modulated. In at least some implementations, while DOEs 2 are switched ON and OFF the image data being injected into the waveguide by the multiplicity of microdisplays is simultaneously modulated to form a composite multi-focal volumetric image that is perceived to a be a single scene to the viewer.

In at least some implementations, by rendering different objects or portions of objects to sub-images relayed to the eye (position 22 in Figure 5C) by the different DOEs 2, objects are placed at different optical viewing distances, or an object can be represented as a 3D volume that extends through multiple planes of focus.

In at least some implementations, the multiplicity of switchable DOEs 2 is switched at a fast enough rate to generate a multi-focal display that is perceived as a single scene.

In at least some implementations, the multiplicity of switchable DOEs 2 is switched at a slow rate to position a single image plane at a focal distance. The accommodation state of the eye is measured and/or estimated either directly or indirectly. The focal distance of the single image plane is modulated by the multiplicity of switchable DOEs in accordance with the accommodative state of the eye. For example, if the estimated accommodative state of the eye suggests that the viewer is focused at a 1 meter viewing distance, the multiplicity of DOEs is switched to shift the displayed image to approximate at 1 meter focus distance. If the eye's accommodative state is estimated to have shifted to focus at, e.g., a 2 meter viewing distance, the multiplicity of DOEs 2 is switched to shift the displayed image to approximate at 2 meter focus distance.

In at least some implementations, the multiplicity of switchable DOEs 2 is switched at a slow rate to position a single image plane at a focal distance. The accommodation state of the eye is measured and/or estimated either directly or indirectly. The focal distance of the single image plane is modulated by the multiplicity of switchable DOEs in accordance with the accommodative state of the eye, and the image data presented by the multiplicity of display elements is switched synchronously. For example, if the estimated accommodative state of the eye suggests that the viewer is focused at a 1 meter viewing distance, the multiplicity of DOEs 2 is switched to shift the displayed image to approximate at 1 meter focus distance, and the image data is updated to render the virtual objects at a virtual distance of 1 meter in sharp focus and to render virtual objects at a virtual distance other than 1 meter with some degree of blur, with greater blur for objects farther from the 1 meter plane. If the eye's accommodative state is estimated to have shifted to focus at, *e.g.*, a 2 meter viewing distance, the multiplicity of DOEs is switched to shift the displayed image to approximate at 2 meter focus distance and the image data is updated to render the virtual objects at a virtual distance of 2 meters in sharp focus and to render virtual objects at a virtual distance other than 2 meters with some degree of blur, with greater blur for objects farther from the 2 meter plane.

In at least some implementations, the DOEs 2 may be used to bias rays outwardly to create a large field of view, at least up to a limit at which light leaks from the planar waveguide(s) 1. For example, varying a pitch of a grating may achieve a desired change in angle sufficient to modify the angles associated with or indicative of a field of view. In some implements, pitch may be tuned to achieve a lateral or side-to-side movement or scanning motion along at least one lateral (*e.g.*, Y-axis). Such may be done in two dimensions to achieve a lateral or side-to-side movement or scanning motion along both the Y-axis and X-axis. One or more acousto-optic modulators may be employed, changing frequency, period, or angle of deflection.

Various standing surface wave techniques (*e.g.*, standing plane wave field) may be employed, for example to dynamically adjust the characteristics of the DOEs 2. For instance standing waves may be generated in a liquid crystal medium trapped between two layers, creating an interference pattern with desired frequency, wavelength and/or amplitude characteristics.

The DOEs 2 may be arranged to create a toe in effect, creating an eye box that tapers from larger to smaller as the light approaches the viewer from the planar waveguide 1. The light box may taper in one or two dimensions (*e.g.*, Y-axis, X-axis, as function of position along the Z-axis). Concentrating light may advantageously reduce luminosity requires or increase brightness. The light box should still be maintain sufficiently large to accommodate expected eye movement.

While various embodiments have located the DOEs 2 in or on the primary planar waveguide 1, other implementations may located one or more DOEs 2 spaced from the primary planar waveguide 1. For example, a first set of DOEs 2 may be positioned between the primary planar waveguide 1 and the viewer, spaced from the the primary planar waveguide 1. Additionally, a second set of DOEs 2 may be positioned between the primary planar waveguide 1 and background or real world, spaced from the the primary planar waveguide 1. Such may be used to cancel light from the planar waveguides with respect to light from the background or real world, in some respects similar to noise canceling headphones.

The various embodiments described above can be combined to provide further embodiments. To the extent that they are not inconsistent with the specific teachings and definitions herein, all of the U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet, including but not limited to U.S. patent application Serial No. 13/915,530, International Patent Application Serial No. PCT/US2013/045267, and U.S. provisional patent application Serial No. 61/658,355, are incorporated herein by reference, in their entirety. Aspects of the embodiments can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments.

These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

CLAIMS

1. A waveguide apparatus, comprising:

a planar waveguide having at least a first end, a second end, a first face, and a second face, the second end opposed to the first end along a length of the waveguide, at least the first and the second faces forming an at least partially internally reflective optical path along at least a portion of the length of the planar waveguide, and

at least one optically diffractive element that interprets the internally reflective optical path to provide a plurality of optical paths between an exterior and an interior of the planar waveguide via the first face thereof at respective positions along at least a portion of the length of the planar waveguide.

2. The waveguide apparatus of claim 1 wherein at least one the diffractive optical element is integral with the planar waveguide.

3. The waveguide apparatus of claim 1 wherein at least one the diffractive optical element is disposed between the first face and the second face of the planar waveguide.

4. The waveguide apparatus of claim 1 wherein at least one the diffractive optical element is positioned at one of the first face or the second face of the planar waveguide.

5. The waveguide apparatus of claim 1 wherein at least one the diffractive optical element is a Braff grating.

6. The waveguide apparatus of claim 1 wherein at least one the diffractive optical element combines a linear diffraction function and a radially circular lens function.

7. The waveguide apparatus of claim 1 wherein at least one the diffractive optical element has a phase profile that is a combination of a linear diffraction grating and a radially symmetric lens.

8. A waveguide array apparatus, comprising:

a set of a plurality of planar waveguides, each of the planar waveguides in the set having at least a first end, a second end, a first face, and a second face, the second end opposed to the first end along a length of the waveguide, at least the first and the second faces forming an at least partially internally reflective optical path along at least a portion of the length of the planar waveguide, and

for each of at least two of the planar waveguides in the set a respective set of diffractive optical elements disposed between the first and the second ends at respective positions along at least a portion of the length of the respective planar waveguide to partially reflect a respective portion of a spherical wave front outwardly from the first face of the respective rectangular waveguide.

9. The waveguide array apparatus of claim 8 wherein at least one the diffractive optical element is integral with respective ones of the planar waveguides.

10. The waveguide array apparatus of claim 8 wherein the elements are disposed between the first face and the second face.

11. The waveguide array apparatus of claim 8 wherein the elements are at one of the first face or the second face.

12. The waveguide array apparatus of claim 8 wherein at least one the diffractive optical element is a Braff grating.

13. The waveguide array apparatus of claim 8 wherein at least one the diffractive optical element combines a linear diffraction function and a radially circular lens function.

14. The waveguide array apparatus of claim 8 wherein at least one the diffractive optical element has a phase profile that is a combination of a linear diffraction grating and a radially symmetric lens.

15. The apparatus and/or system as shown and described above.

ABSTRACT OF THE DISCLOSURE

A waveguide apparatus includes a planar waveguide and at least one optical diffraction element (DOE) that provides a plurality of optical paths between an exterior and interior of the planar waveguide. A phase profile of the DOE may combine a linear diffraction grating with a circular lens, to shape a wave front and produce beams with desired focus. Waveguide apparati may be assembled to create multiple focal planes. The DOE may have a low diffraction efficiency, and planar waveguides may be transparent when viewed normally, allowing passage of light from an ambient environment (*e.g.*, real world) useful in augmented reality systems. Light may be returned for temporally sequentially passes through the planar waveguide. The DOE(s) may be fixed or may have dynamically adjustable characteristics. An optical coupler system may couple images to the waveguide apparatus from a projector, for instance a biaxially scanning cantilevered optical fiber tip.

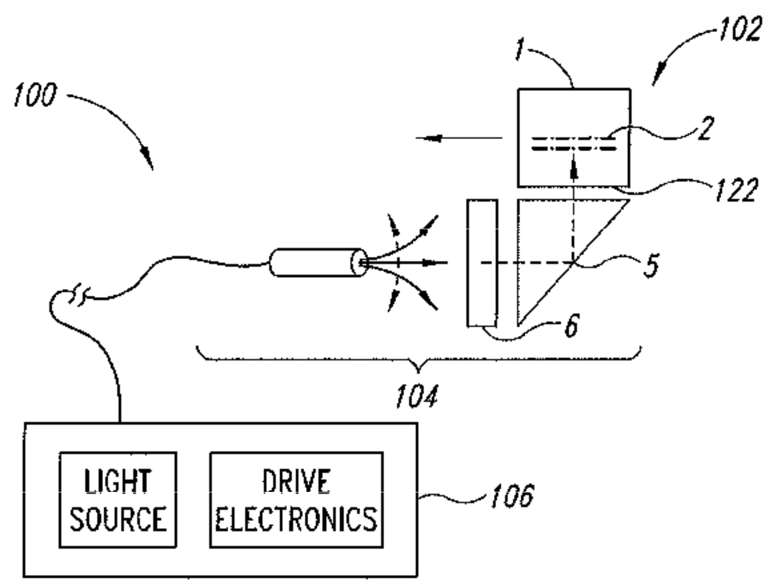

100
102
1
2
122
5
6
104
LIGHT SOURCE
DRIVE ELECTRONICS
106

FIG. 1

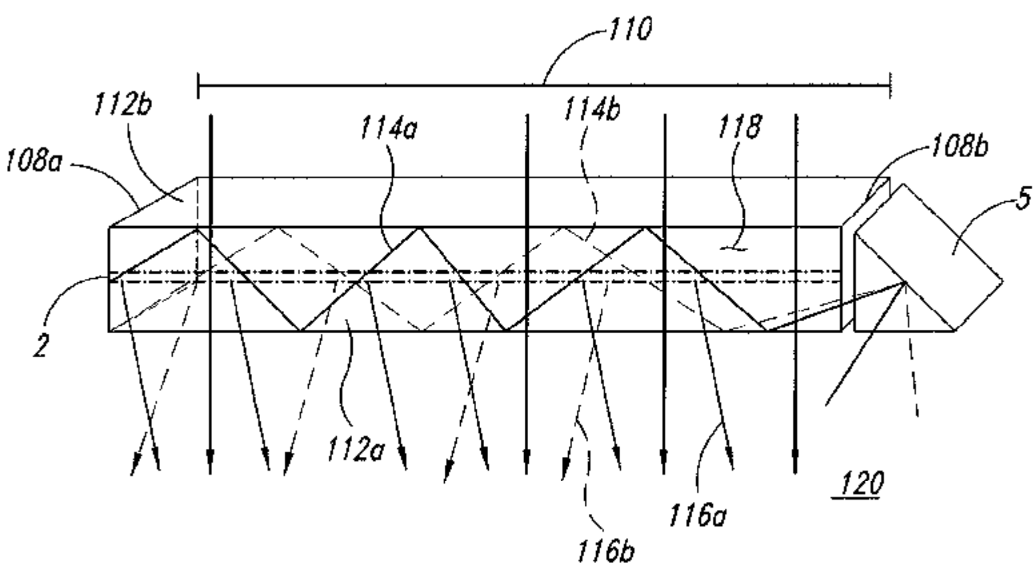

110
112b
108a
114a
114b
118
108b
5
2
112a
120
116a
116b

FIG. 2

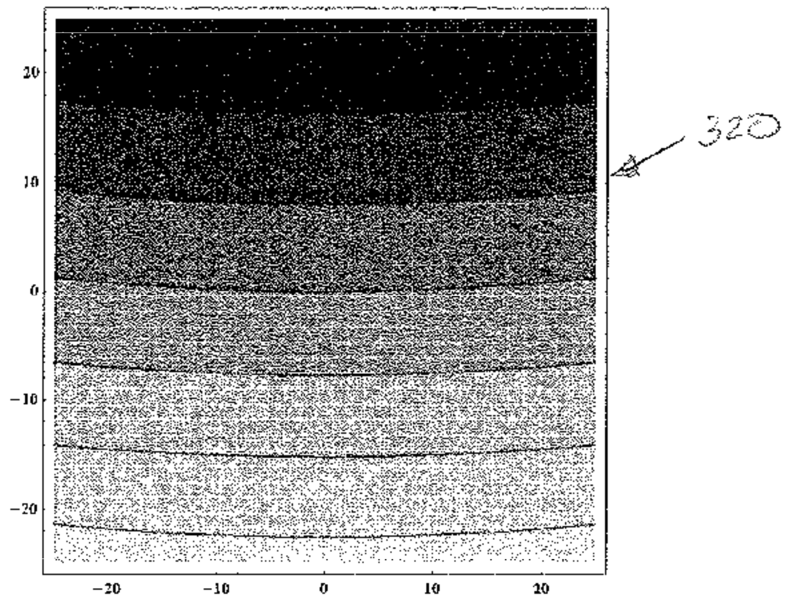


FIG. 3C

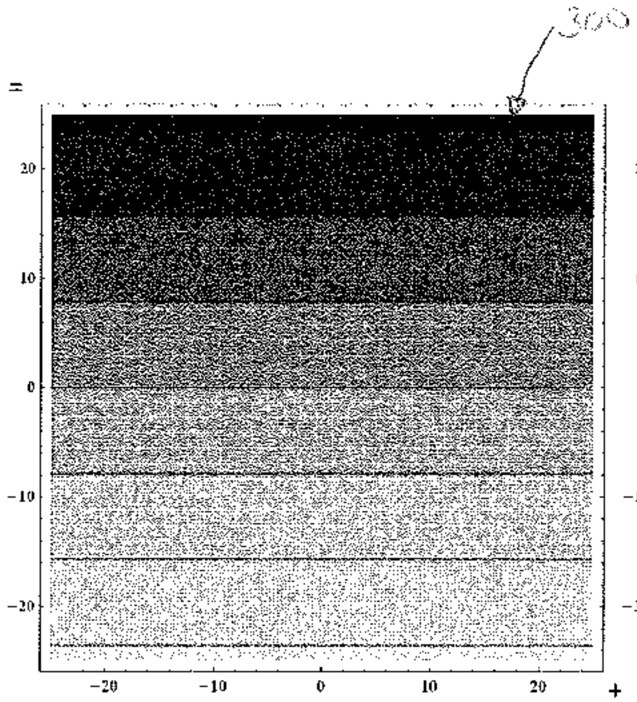


FIG. 3A

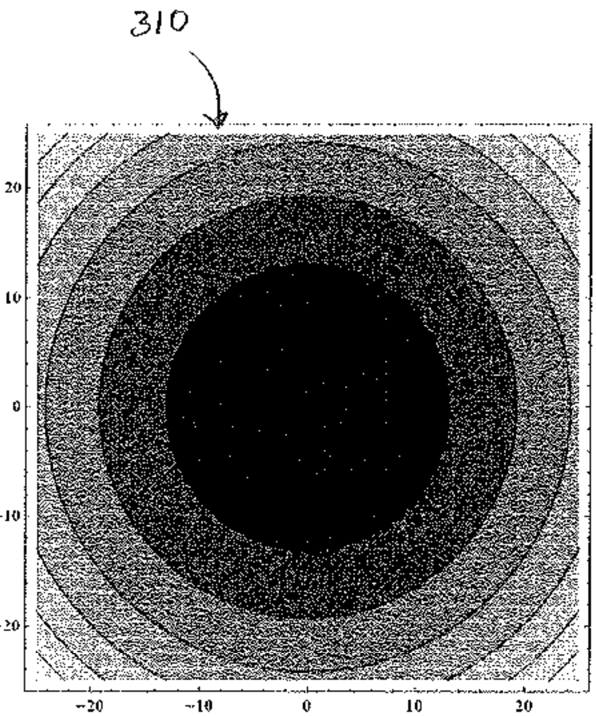


FIG. 3C

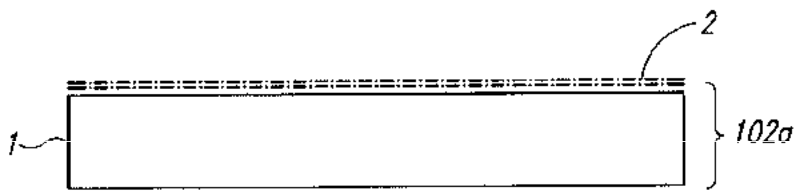


FIG. 4A

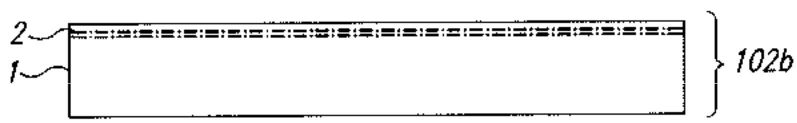


FIG. 4B

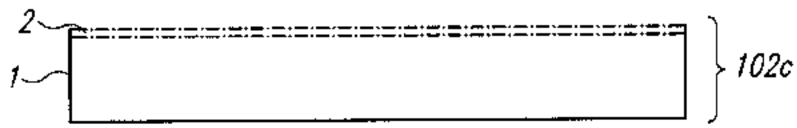
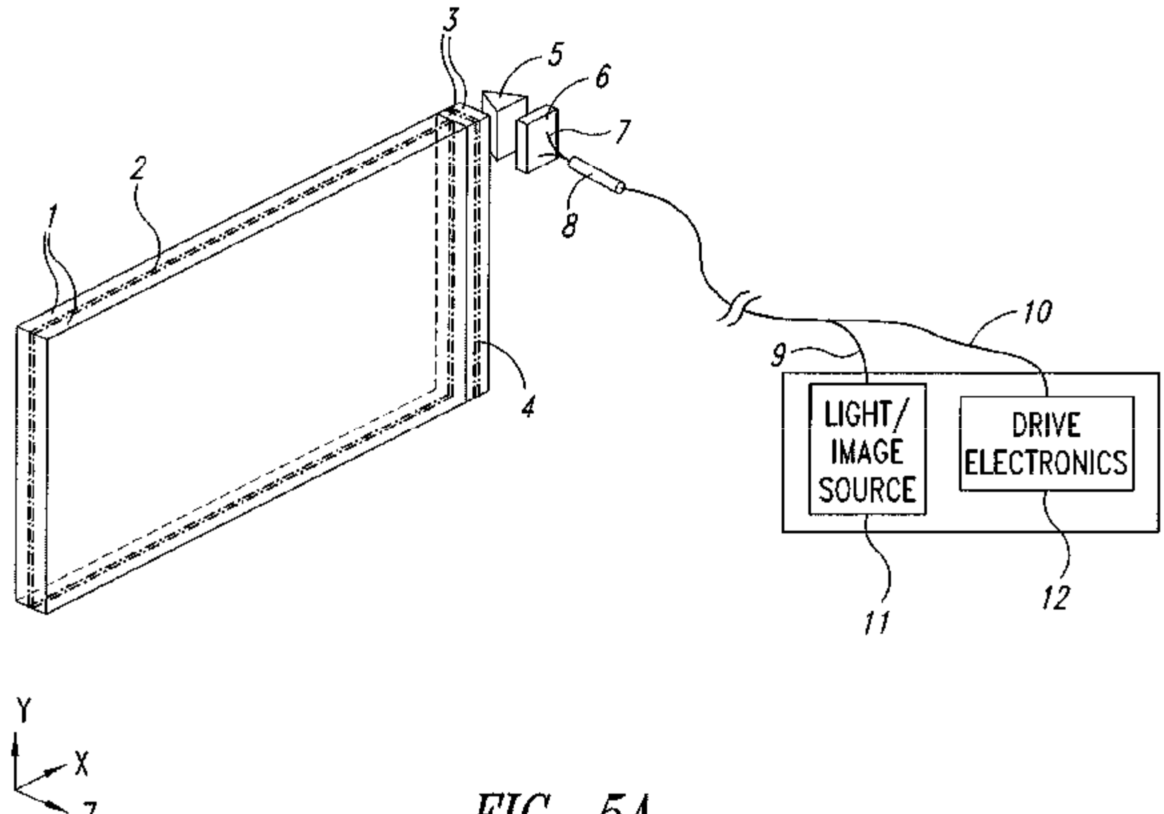


FIG. 4C


3
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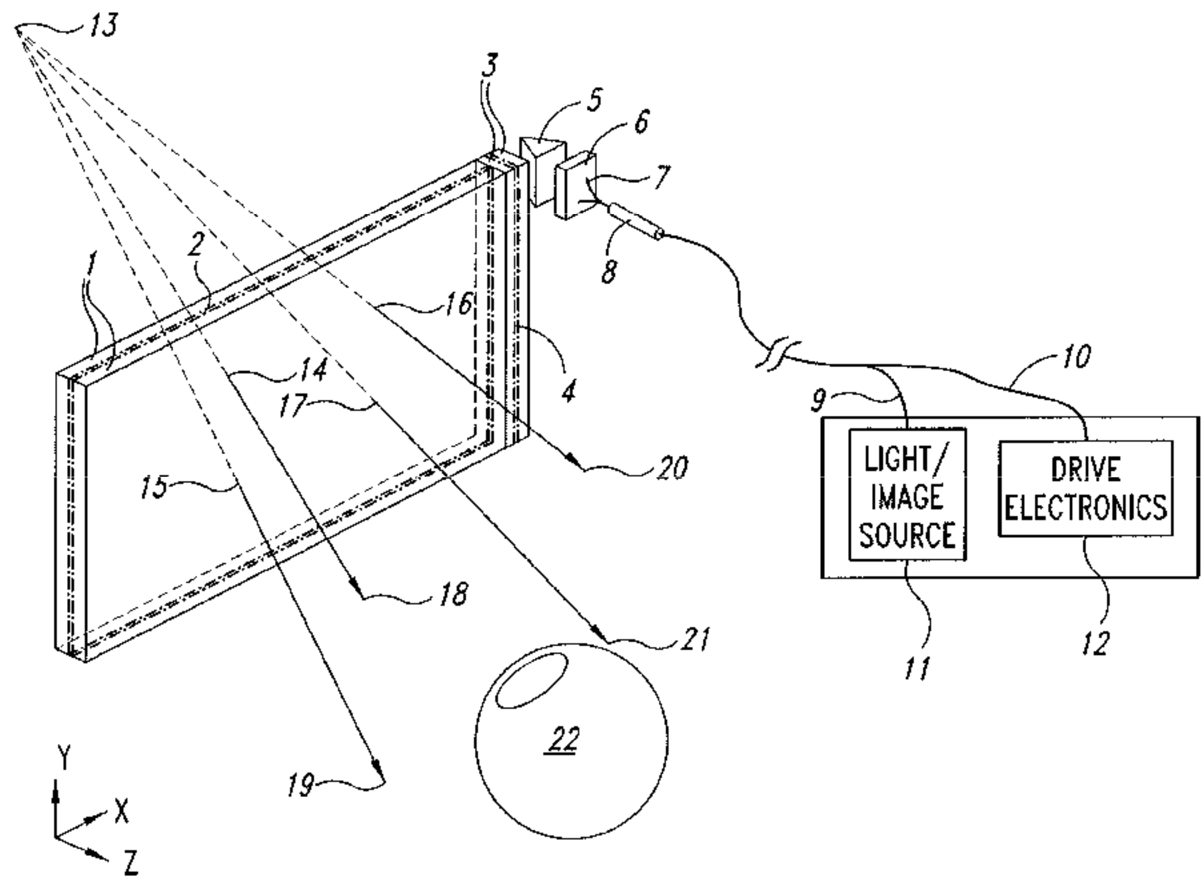
7
2
1
8
4
10
9
LIGHT/
IMAGE
SOURCE
DRIVE
ELECTRONICS
11
12
Y
X
Z

FIG. 5A



13
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16
14
17
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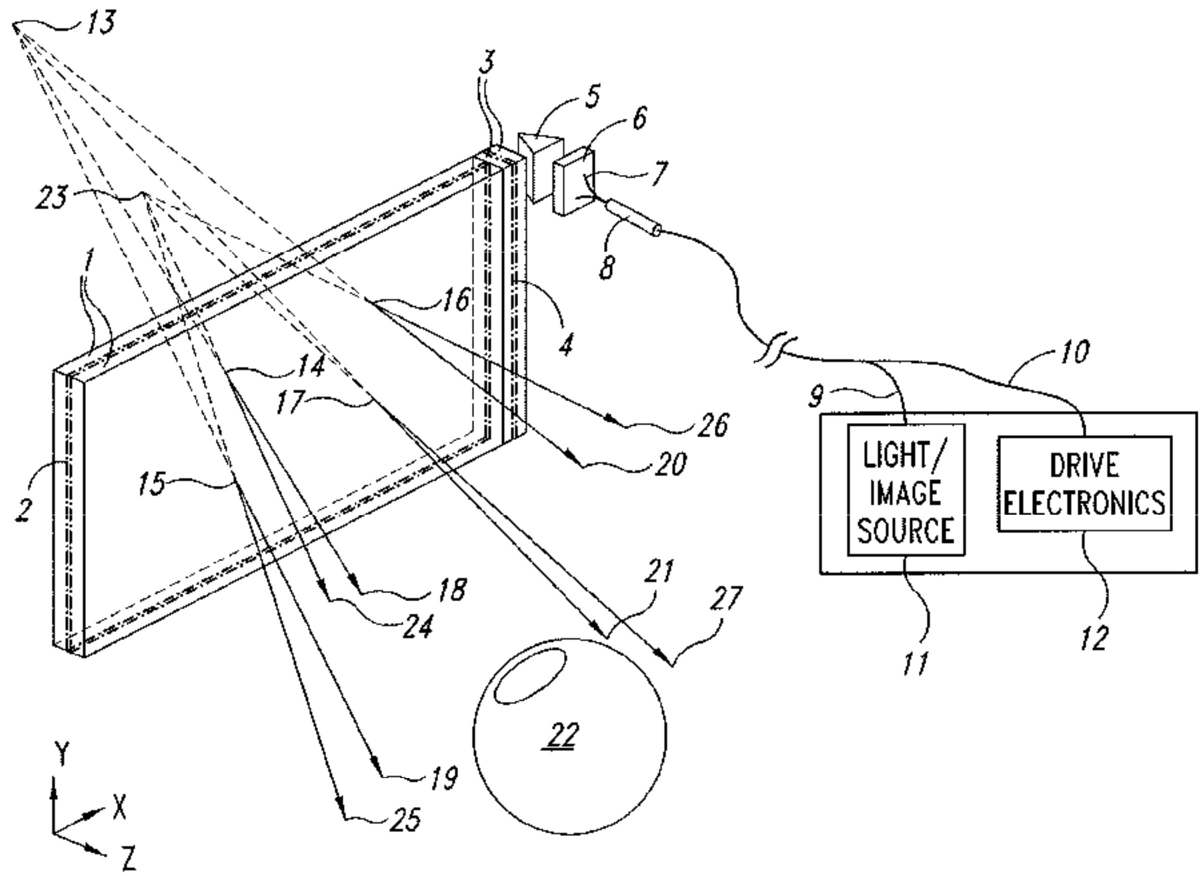
LIGHT/
IMAGE
SOURCE
DRIVE
ELECTRONICS
15
18
21
11
12
22
19
Y
X
Z

FIG. 5B


13
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16
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14
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10
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26
20
LIGHT/
IMAGE
SOURCE
DRIVE
ELECTRONICS
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24
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19
25
Y
X
Z

FIG. 5C

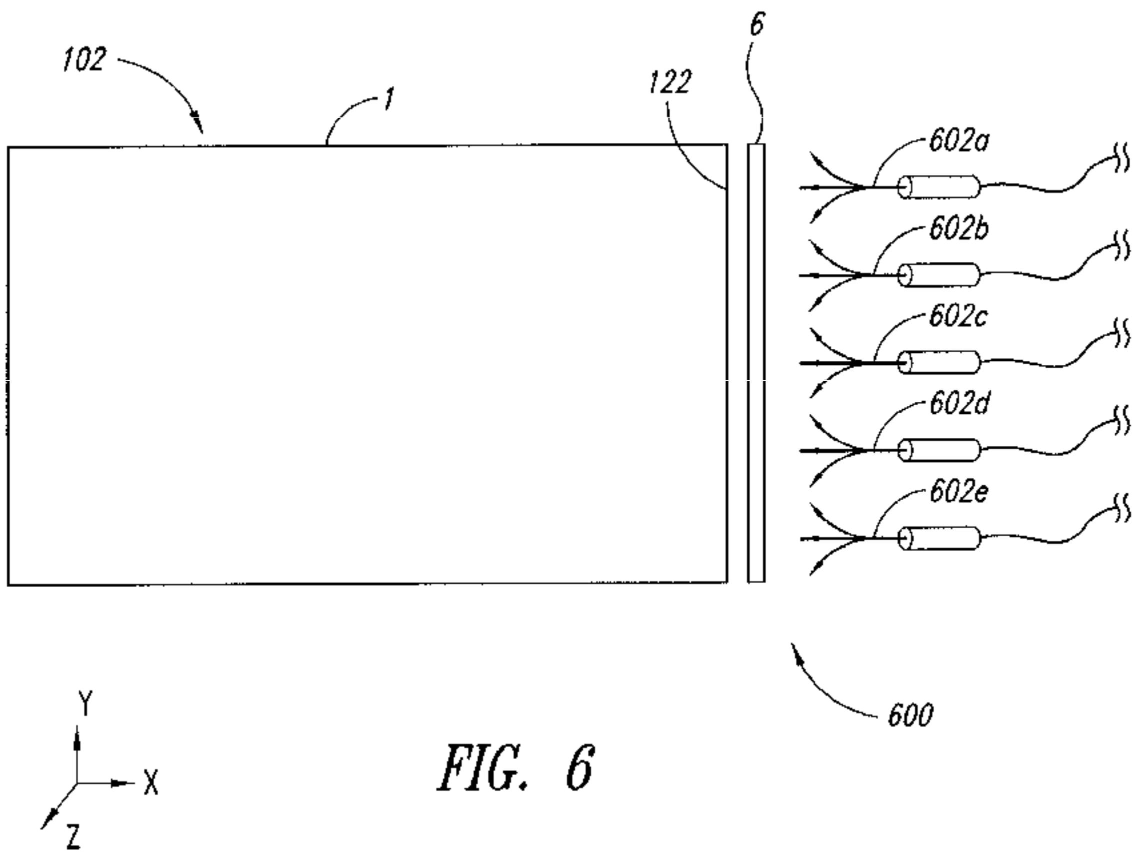


FIG. 6

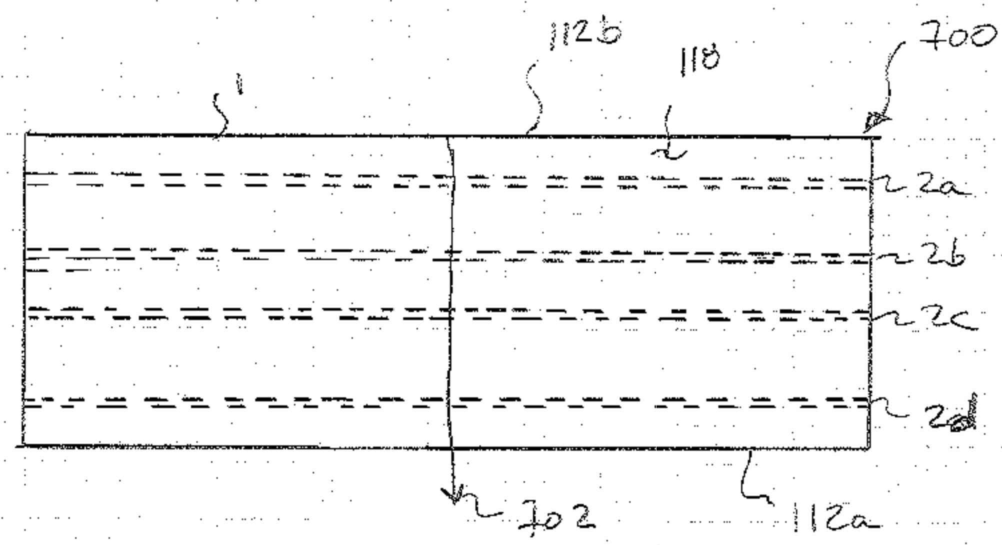
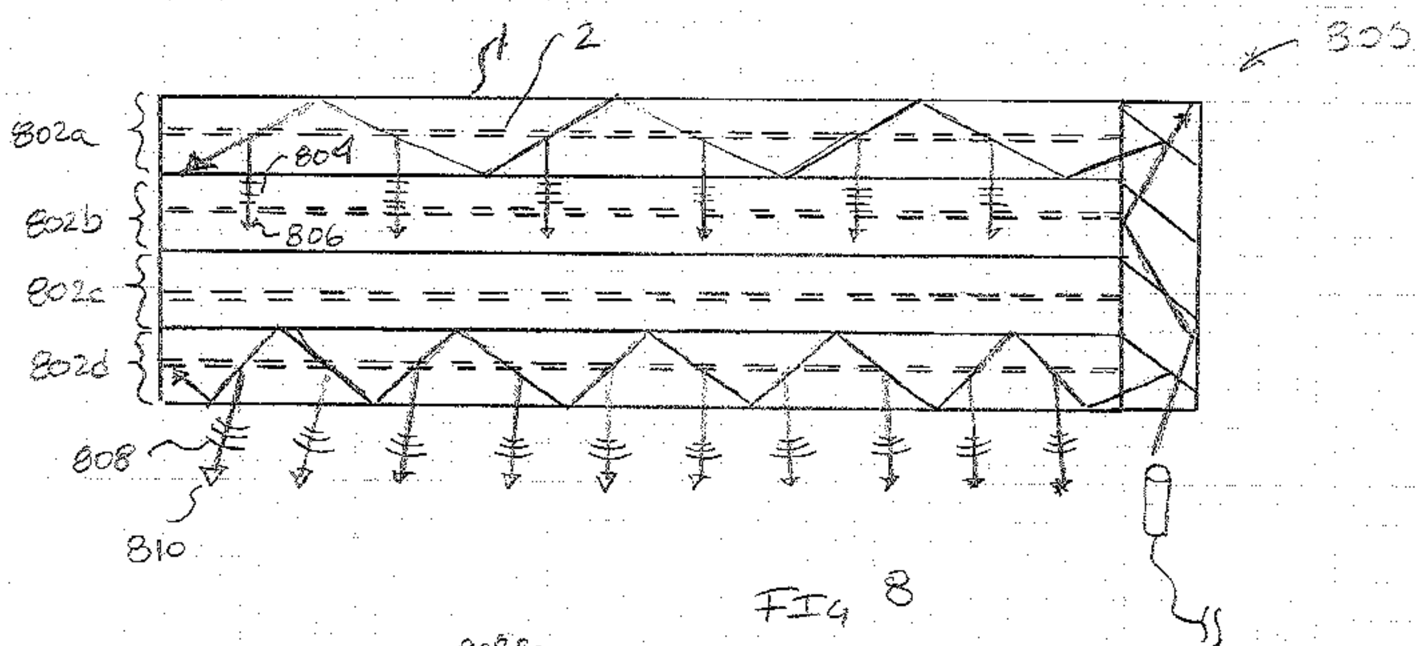


FIG. 7


800
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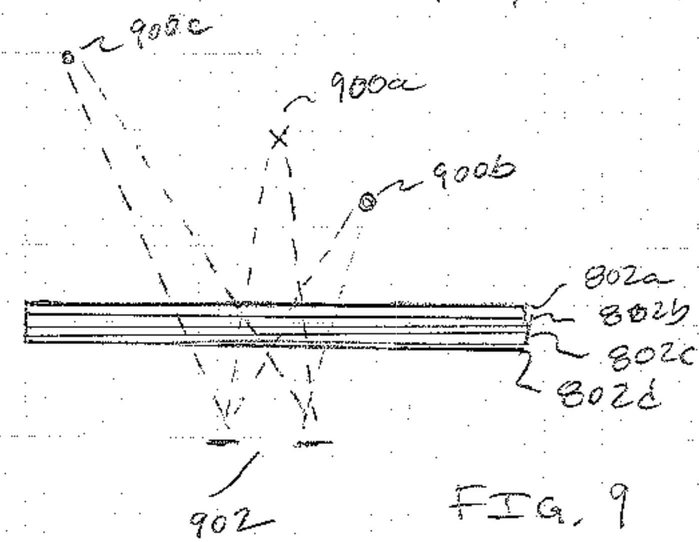
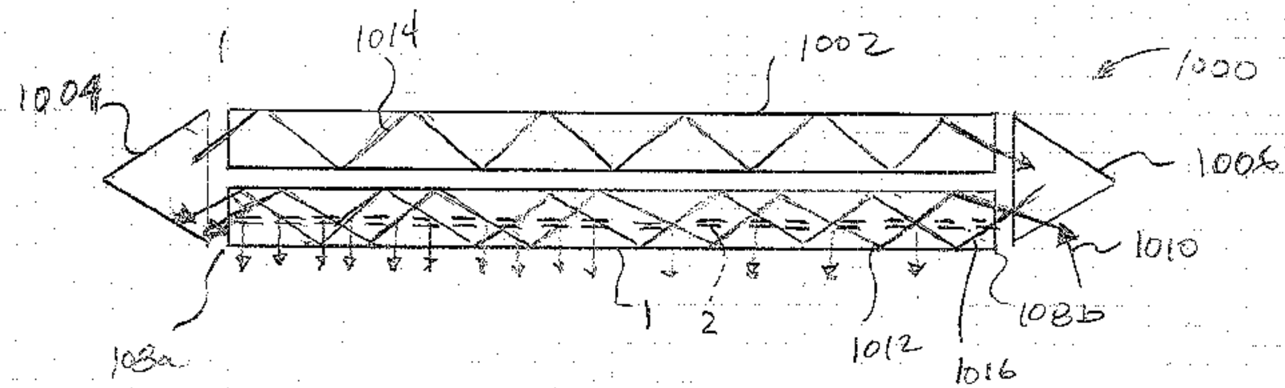
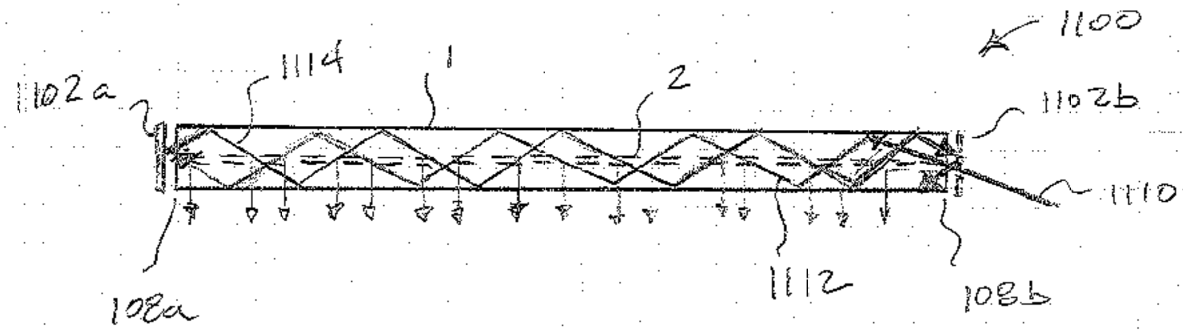
2
802a
802b
802c
802d
804
806
808
810
FIG 8


900a
900b
900c
802a
802b
802c
802d
902
FIG. 9



1000
1002
1004
1006
1010
1012
1014
1016
1
2
108a
108b

FIG. 10



1100
1102a
1102b
1110
1112
1114
1
2
108a
108b

FIG. 11

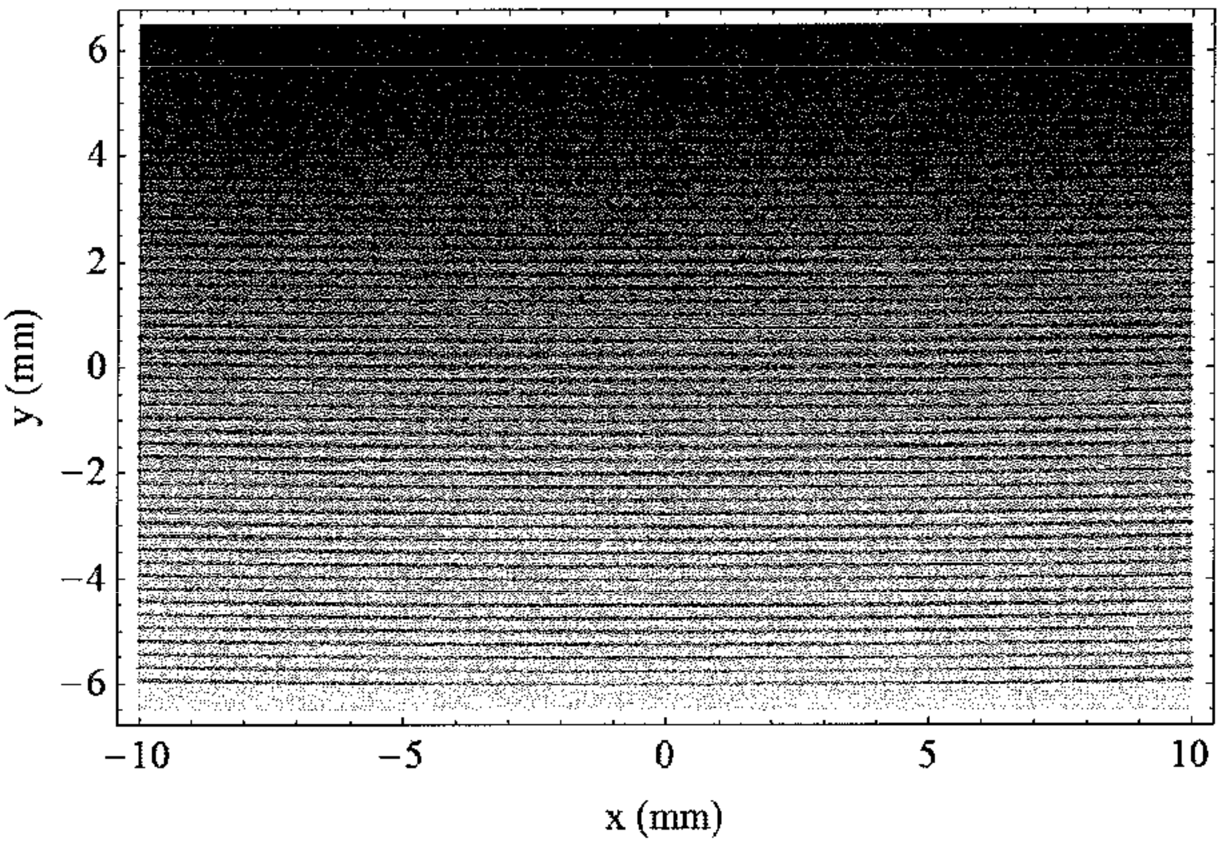


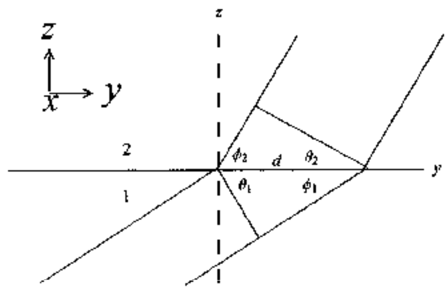
FIG 12

EDGE Theoretical Performance Notes

Mathew D Watson, 28 February 2013

$k_j = \frac{2\pi}{\lambda_j}$, where j is the region index. The index 0 is used to indicate free space (air).

In[2]:=



$k_2\, d \sin(\theta_2) - k_1\, d \sin(\theta_1) = m\, 2\pi$

$\frac{2\pi}{\lambda_1} \sin(\theta_2) - \frac{2\pi}{\lambda_2} \sin(\theta_1) = m\, \frac{2\pi}{d}$

$\frac{2\pi}{\lambda_2} \sin(\theta_2) = m\, \frac{2\pi}{d} + \frac{2\pi}{\lambda_1} \sin(\theta_1)$

$k_2 \sin(\theta_2) = m\, \frac{2\pi}{d} + k_1 \sin(\theta_1)$

$k_{2\,y} = m\, \frac{2\pi}{d} + k_{1\,y}$

$k_{2\,y} = m\, k_g + k_{1\,y}$

Alternative formulation normalized using the free space wavelength.

$\vec{h}_j = \frac{\vec{k}_j}{k_0}$

$h_j = \frac{k_j}{k_0} = n_j$

$h_g = \frac{k_g}{k_0} = \frac{\lambda_0}{d}$

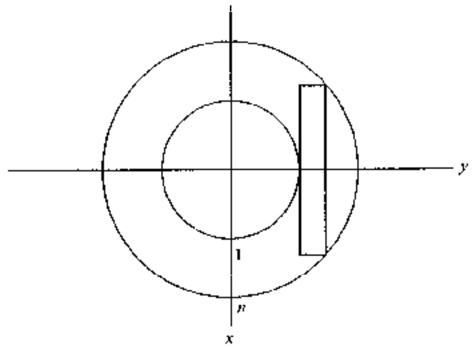
$h_{2\,y} = m\, h_g + h_{1\,y}$,

where $h_{j\,y} = h_j \sin(\theta_j)$

If $|h_{2\,y}| \le h_2$, then the wave associated with $\vec{h}_2$ is not evanescent.

For the substrate guided wave, the rectangle in the following diagram indicates the region of allowed projections of $\vec{h}$ into the x y plane. The outer circle has radius n, and indicates a wave vector parallel to the x y plane. The inner circle has radius 1 and indicates the TIR boundary.

FIG. 13A



In the normalized representation, $\vec{h}$ is a vecotor of magnitude n independent of free space wavelength. When the index is 1, the components are the direction consines of $\vec{k}$.

$$k_x^2 + k_y^2 + k_z^2 = k_0^2$$
$$h_x^2 + h_y^2 + h_z^2 = n^2$$

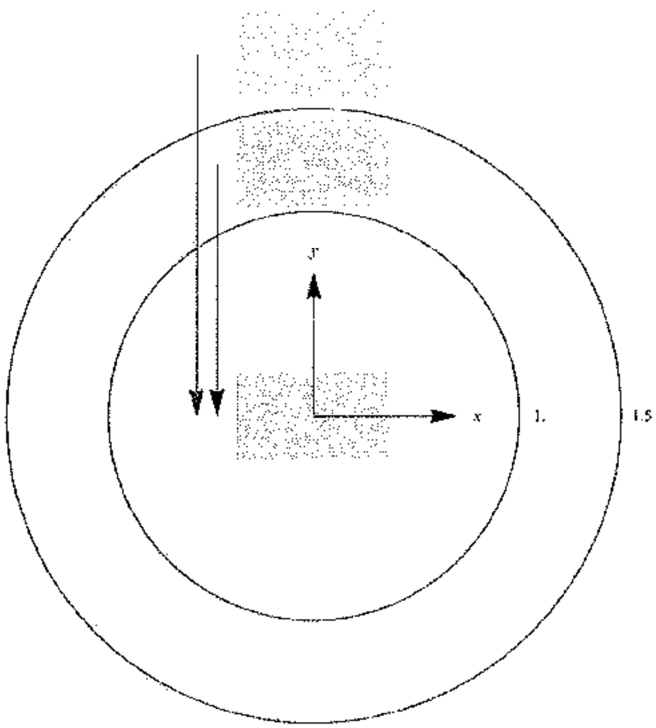
The wavelengths used to design an earlier fiber scanner lens (ref. sfe-06aa.zmx) were 443, 532, and 635 nm. The red and blue wavelengths are used in the following calculation.

The following diagram shows a plot of normalized wave vector regions projected into the x y plane (i.e. parallel to the substrate). The gray rectangle represents the eye field of view. The red and blue rectangles represent the waveguide vector projections required to produce the eye field of view. The red and blue arrows indicate the deflection provided by the grating. The unit radius circle represents the TIR constraint for a guided wave in the substrate, and the 1.5 radius circle represents a wave propagating parallel to the substrate when the index $n = 1.5$. Wave vectors propaging between the two circles are allowed. This plot is for the substrate oriented vertically, a 50° diagonal (16 x 9 format) eye field of view, and a 0.36 μm grating line spacing. Note that the blue rectangle lies inside the region of allowed region, whereas the red rectangle lies in the evanescent region.

FIG. 13B

In[2]:= f[0, 50, .36]

Out[2]=

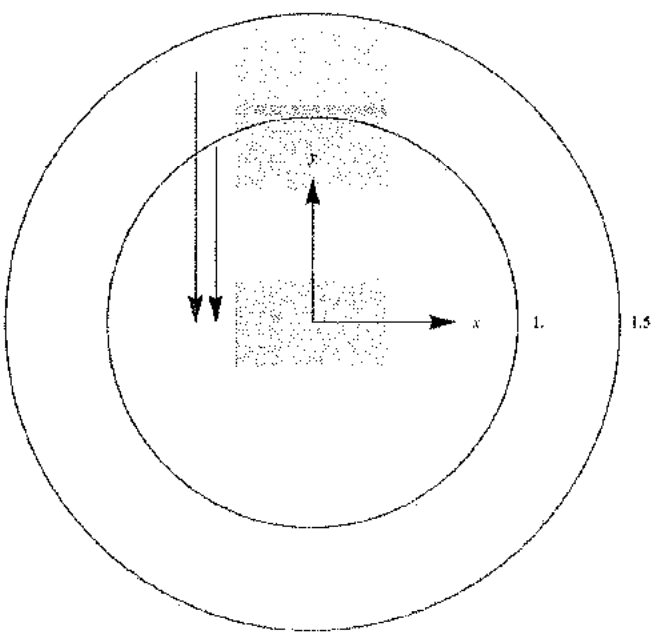


By increasing the groove spacing to 5.2 μm the red wave vectors can be brought inside the allowed region, but then a majority of the blue wave vectors do not TIR.

In[3]:= f[0, 50., 0.52]

FIG. 13C

Out[3]=



Tilting the substrate with respect to the eye is equivalent to biasing the eye field of view with respect to the substrate. This plot shows the effect of tilting the waveguide 45° and increasing the groove width to 0.85 μm. Note that the

FIG. 13D

difference between the grating arrows is less, and that both the red and blue wavevectors fall substatially within the allowed region.

In[4]:= `f[45., 50., 0.85]`

Out[4]=

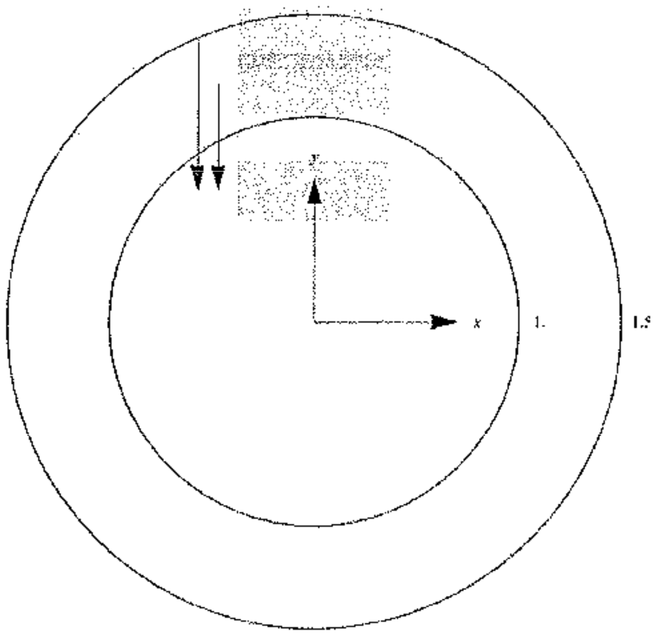


FIG. 13E