DIE OUTLINE DESIGN STRATEGY FOR AUGMENTED REALITY LIGHTGUIDE COMBINERS

BACKGROUND

Field

[0001] Embodiments of the present disclosure generally relate to augmented reality waveguide combiners.

Description of the Related Art

[0002] Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

[0003] Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

[0004] One such challenge is that waveguide combiners often have undesired light paths of incident light that include reflections off of die edges that couple to a user's field of view. Waveguide combiners are used to assist in overlaying virtual images. Generated light is in-coupled into a waveguide combiner, propagated through the augmented waveguide combiner, out-coupled from the augmented waveguide combiner, and overlaid on the ambient environment. The undesired light paths degrade the virtual-image contract and/or result in artifacts such a light streaks.

[0005] Therefore, there is a need in the art for a waveguide combiner that can prevent the undesired light paths from coupling to the user's field of view.

SUMMARY

[0006] According to one or more embodiments, a waveguide includes a waveguide substrate, the waveguide substrate having a first surface and a second surface opposing the first surface, the first and second surfaces are connected by an edge, the edge having an angled portion with a re-direction angle, and an in-coupler grating disposed over the first surface or the second surface, wherein the in-coupler grating is operable to diffract in-coupled light on a first incident path to the angled portion of the edge that absorbs a first portion of the in-coupled light and directs a second portion of in-coupled light to another portion of the edge at least partially avoiding an out-coupler grating according to the re-direction angle.

[0007] According to one or more embodiments, a waveguide includes a waveguide substrate, the waveguide substrate having a first surface and a second surface opposing the first surface, the first and second surfaces are connected by an edge, the edge having an angled portion with a re-direction angle, an in-coupler grating disposed over the first surface or the second surface, wherein the in-coupler grating is operable to diffract in-coupled light on a first incident path to the angled portion of the edge that absorbs a first portion of the in-coupled light and directs a second portion of in-coupled light to an out-coupler grating according to the re-direction angle of the angled portion, and the out-coupler grating, wherein the out-coupler grating diffracts the second portion to remain under total internal reflection (TIR) within the waveguide substrate.

[0008] According to one or more embodiments a waveguide includes a waveguide substrate, the waveguide substrate having a first surface and a second surface opposing the first surface, the first and second surface are connected by an edge, the edge having an curved portion with an angle of curvature, an in-coupler grating disposed over the first surface or the second surface, wherein the in-coupler grating is operable to diffract in-coupled light on a first incident path to the curved portion, the in-coupled light having a red field of view (FOV), a green FOV, and a blue FOV, the curved portion absorbs a first portion of the red FOV, the green FOV, and the blue FOV, and directs a second portion of the red FOV, the green FOV, and the blue FOV to an out-coupler grating according to the angle of curvature of the curved portion, and the out-coupler grating, wherein the out-coupler grating diffracts the second portion to remain under total internal reflection (TIR) within the waveguide substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

[0010] FIG. 1A is a perspective, frontal view of a waveguide according to one or more embodiments.

[0011] FIG. 1B is a cross-sectional view of the waveguide having the arrangement shown in FIG. 1A according to one or more embodiments.

[0012] FIG. 2 illustrates example instances of incident light paths that out-couple to the field of view of a user and cause edge scattering artifacts according to one or more embodiments.

[0013] FIG. 3A is a perspective, frontal view of a waveguide used to prevent incident light from coupling with the center field of view of an image according to one or more embodiments.

[0014] FIG. 3B illustrates a k-space plot of a waveguide having the arrangement shown in FIG. 3A according to one or more embodiments.

[0015] FIG. 4A is a perspective, frontal view of a waveguide used to prevent incident light from coupling with the center field of view of an image according to one or more embodiments.

[0016] FIG. 4B illustrates a k-space plot of a waveguide having the arrangement shown in FIG. 4A according to one or more embodiments.

[0017] FIG. 5A is a perspective, frontal view of a waveguide used to prevent incident light from coupling with the center field of view of an image according to one or more embodiments.

[0018] FIG. 5B illustrates a k-space plot of a waveguide having the arrangement shown in FIG. 5A according to one or more embodiments.

[0019] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0020] Embodiments herein relate to waveguide combiners. In particular, embodiments herein relate to a waveguide combiner that is shaped to prevent undesired incident light paths from coupling to a user's field of view.

[0021] FIG. 1A is a perspective, frontal view of a waveguide 100. FIG. 1B is a cross-sectional view of the waveguide having the arrangement shown in FIG. 1A according to one or more embodiments. It is to be understood that the waveguide 100 described herein is an exemplary waveguide and that other waveguides may be used with or modified to accomplish aspects of the present disclosure. In one embodiment, which can be combined with other embodiments described herein, the waveguide 100 is a waveguide combiner, such as an augmented reality waveguide combiner. In another embodiment, which can be combined with other embodiments described herein, the waveguide 100 is a flat optical device, such as a metasurface. The waveguide 100 includes a first surface 103 that opposes a second surface 114 that are connected by an edge 105. The substrate 101 (i.e., waveguide substrate) has a substrate refractive index (RI) n_{sub}. The substrate 101 may be formed from any suitable material, provided that the substrate 101 can adequately transmit light in a selected wavelength or wavelength range and can serve as an adequate support for the waveguide 100 described herein. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, and combinations thereof. In some embodiments, which may be combined with other embodiments described herein, the substrate 101 includes glass, silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), fused silica, quartz, sapphire (Al_2O_3), silicon carbide (SiC), lithium niobate ($LiNbO_3$), indium tin oxide (ITO), or combinations

thereof. In other embodiments, which may be combined with other embodiments described herein, the substrate 101 includes high-refractive-index glass. The high-refractive-index glass includes greater than 2 percent by weight of lanthanide (Ln), titanium (Ti), tantalum (Ta), or combinations thereof.

[0022] The waveguide 100 includes a plurality of structures 102. The structures 102 may be disposed on the first surface 103 or the second surface 114 of the substrate 101. The structures 102 are nanostructures have a sub-micron critical dimension, e.g., a width less than 1 micrometer. Regions of the structures 102 correspond to one or more gratings 104. In one embodiment, which can be combined with other embodiments described herein, the waveguide 100 includes at least a first grating 104a corresponding to an in-coupler grating and a third grating 104c corresponding to an out-coupler grating. In another embodiment, which can be combined with other embodiments described herein, the waveguide 100 further includes a second grating 104b. The second grating 104b corresponds to a pupil expansion grating or a fold grating. The structures 102 have a grating RI n_{grat}. A grating material of the structures 102 results in the grating RI n_{grat}. The grating material may include, but is not limited to, one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate (Cd_2SnO_4), or silicon carbon-nitride (SiCN) containing materials.

[0023] The first grating 104a may have a first grating period Λ_{IC} of about 250 to about 500 nm. The third grating 104c may have a second grating period Λ_{OC} of about 250 to about 500 nm. The first grating 104a may have a first grating angle θ_{IC}. In some embodiments, the first grating angle θ_{IC} is the angle between a vector 110 normal to the structures 102 of the first grating 104a and the horizontal axis 108 (the x-axis). The first grating angle θ_{IC} may be any angle of about 0 to about 360°. The third grating 104c may have a second grating angle θ_{OC}. The second grating angle θ_{OC} is the angle between a vector 112 normal to the structures 102 of the third grating 104c and the horizontal axis 108. The second grating angle θ_{OC} may be any angle of about 0 to about 360°.

[0024] The waveguide 100 may experience edge scattering artifacts such as light streaks that degrade the virtual-image displayed to a user. For example the waveguide 100 may experience undesired incident light paths that include reflections off the edges 105 of the substrate 101 that out-couple to a user's field of view. Conventionally, to prevent light streaks, the edges 105 are coated with black paint to absorb incident light that is scattered to the edges. However, the black paint is ineffective in completely absorbing the incident light at the edges.

[0025] FIG. 2 illustrates example instances of incident paths that out-couple to the field of view of a user and cause edge scattering artifacts according to one or more embodiments. As illustrated in FIG. 2, example incident paths that may cause edge scattering artifacts include, but are not limited to, a first incident path P1, a second incident path P2, and a third incident path P3. Each of the incident paths P1-P3 are located in the center of the field of view of the displayed virtual image. Although three undesired incident paths are shown in FIG. 2, it is understood that there are multitude of incident light paths. Furthermore, although FIG. 2 only illustrates light paths in the center of the field of view of the image, it is understood that are incident light paths across the entire field of view of the virtual image. For example, the first incident path P1 includes first in-coupled light $P1_1$ that is on the first incident path P1 that is in-coupled and directed to the edge 105 by the first grating. Due to the black coating of the edge 105, a first portion of the first in-coupled light $P1_1$ is absorbed by the edge 105, and a second portion of the first in-coupled light $P1_1$ (i.e., defined herein as first edge-reflected light $P1_2$) is reflected. The first edge-reflected light $P1_2$ is directed to the third grating 104c and is out-coupled to the field of view of the user based on the shape of the edge 105.

[0026] The second incident path P2 includes second in-coupled light $P2_1$ that is on the second incident path P2 and is diffracted (directed) by the second grating 104b to the edge 105. Due to the black coating of the edge 105, a first portion of the second in-coupled light $P2_1$ is absorbed by the edge 105. A second portion of the second in-coupled light $P2_1$ (i.e., defined herein as the second edge-reflected light $P2_2$) is reflected. The second edge-reflected light $P2_2$ is directed to the third grating 104c and is out-coupled by third grating 104c to the field of view of the user based on the shape of the edge 105. The third incident path P3 includes third in-coupled light $P3_1$ that is on the third incident path P3 and is diffracted to the edge 105 by the third grating 104c.

Due to the black coating of the edge 105, a first portion of the third in-coupled light $P3_1$ is absorbed by the edge 105. A second portion of the third in-coupled light $P3_1$ (i.e., defined herein as third edge-reflected light $P3_2$) is reflected. The third edge-reflected light $P3_2$ is directed to the third grating 104c and is out-coupled to the field of view of the user based on the shape of the edge 105.

[0027] Embodiments herein relate to preserving the quality of the virtual image by changing a shape of the edge 105 of the substrate 101 based on the undesired light paths experienced by the waveguide 100 to re-direct the edge-reflected light away from the field of view of the user to prevent degradation of the virtual image and/or light streaks.

[0028] In one example, the shape of the edge 105 of the substrate 101 can be changed so that the edge-reflected light of the center of the field of view of the virtual image completely avoids the third grating 104c (output coupling grating). FIG. 3A is a perspective, frontal view of a waveguide 300 used to prevent incident light from coupling with the center field of view of a user according to one or more embodiments. In one or more embodiments, as illustrated in FIG. 3A, the edge 105 of the substrate 101 is shaped to include an angled portion 302 located near the first grating 104a (i.e., on the first incident path P1). The angled portion 302 may form a first re-direction angle θ_1 measured with respect to the horizontal axis 108 (the x-axis). The first re-direction angle θ_1 may be any angle of about 0 to about 360° and is determined based on the geometry and layout of the first grating 104a and the third grating 104c. Advantageously, as shown in FIG. 3A, the angled portion 302 is angled such that the first edge-reflected light $P1_2$ is re-directed and avoids the third grating 104c. Stated otherwise, the first re-direction angle θ_1 causes the first edge-reflected light $P1_2$ to at least partially avoid the third grating 104c, and thus, is not out-coupled to the field of view of the user. In particular, the first in-coupled light $P1_1$ of the first incident light path P1 is in-coupled by the first grating 104a and propagated to the edge 105. The edge 105 absorbs a first portion of the first in-coupled light $P1_1$, and the first edge-reflected light $P1_2$ (a second portion of the first in-coupled light $P1_1$) reflects off the angled portion 302. However, due to the first re-direction angle θ_1 of the angled portion 302, the first edge-reflected light $P1_2$ avoids the third grating 104c. The first edge-reflected light $P1_2$ remains in total internal reflection (TIR). The first edge-reflected light $P1_2$ is not out-coupled to the user. In one embodiment, the first edge-

reflected light $P1_2$ avoids the third grating 104c (i.e., the out-coupler grating) and is directed to another portion of the edge 105 according to the first re-direction angle θ_1. The first edge-reflected light $P1_2$ undergoes an additional interaction with the black coating of the edge 105 of the substrate 101. The first edge-reflected light $P1_2$ is not out-coupled to the user because it is absorbed by the edge 105 due to the additional interaction. Therefore, the angled portion 302 causes the first edge-reflected light $P1_2$ to remain in TIR with the substrate 101.

[0029] Although FIG. 3A includes one angled portion 302 used to redirect a single incident light path, this is for example purposes only. It is understood that the edge of the substrate 101 of waveguide 300 can include multiple angled portions that cause each incident path in the center of the field of view of the virtual image to at least partially avoid the third grating 104c. For example, the edge 105 of the substrate 101 of waveguide 300 can include an angled portion located along the second incident path P2. The angled portion along the second light path P2 would have an angle such that the second edge-reflected light $P2_2$ also avoids the third grating 104c.

[0030] FIG. 3B illustrates a k-space plot of a waveguide having the arrangement shown in FIG. 3A according to one or more embodiments. The sequence of incident light in-coupling with the waveguide 300, reflecting off the angled portion 302, and at least partially avoiding out-coupling with the center of the field of view of the user is represented by k-space diagram 350. The k-space diagram 350 schematically represents the waveguide 300 by an outer circle 352 and the material surrounding the waveguide 300 (e.g., air or another optical element) is represented by inner circle 354. The inner circle 354 represents conditions for light to propagate in air. The outer circle 352 corresponds to the angle condition for light to propagate within the substrate 101. The center of the field of view of the user is represented by field of view (FOV) circle 353. The annulus between the concentric inner circle 354 and outer circle 352 corresponds to the TIR condition for light to propagate in the waveguide 300.

[0031] As illustrated in FIG. 3B, in operation, white incident light, such as first in-coupled light $P1_1$ is in-coupled by the first grating 104a and undergoes total-internal-reflection (TIR) through the waveguide 100 to the edge 105. The first in-coupled light $P1_1$ propagates internally within the waveguide 300 to the edge 105 of the substrate 101, as represented by a vector 360a extending from the inner circle 354 to the outer

circle 352. A blue channel light (wavelengths of 380 nm to about 495 nm), a green channel light (wavelength of about 495 nm to about 590 nm), a red channel light (wavelength of about 590 nm to about 750 nm) propagate under total internal reflection (TIR) at different decay rates.

[0032] As shown in Figure 3B, at a first TIR state 357 the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue field of view (FOV) c1, a green FOV c2, and a red FOV c3 offset from each other.

[0033] A portion of the beams of the light channels are absorbed by the black coating of the edge 105 and a portion of the beams of the light channels (the first edge-reflected light $P1_2$) reflects off the angled portion 302. The portion of the reflected beams of the light channels are as represented by a vector 360b extending from the inner circle 354 to the outer circle 352. Due to the angled portion 302, as shown in Figure 3B, at a second TIR state 367 the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV c1, a green FOV c2, and a red FOV c3 offset from each other. The portion of the reflected beams of the light channels avoids the third grating 104c and remains in the outer circle 352 (i.e., in total internal reflection of the substrate 101). Thus, none of the first edge-reflected light $P1_2$ is out-coupled to the center of the field of view of the user.

[0034] In some examples, it may not be possible to shape the edge 105 of the substrate 101 to prevent the edge-reflected light in the center of the field of view of the virtual image from reaching the third grating 104c. In some embodiments, the edge 105 of the substrate 101 may be angled so that the edge-reflected light in the center of the field of view of the virtual image light is diffracted by the third grating 104c and remains in TIR.

[0035] FIG. 4A is a perspective, frontal view of a waveguide 400 used to prevent incident light from coupling with the center of the field of view of a user. In one or more embodiments, as illustrated in FIG. 4A, the edge 105 of waveguide 400 includes an angled portion 402 positioned on the first incident path P1. The angled portion 402 may form a second re-direction angle θ_2 measured with respect to the horizontal axis 108. The second re-direction angle θ_2 may be any angle of about 0 to about 360° and

is determined based on the geometry and layout of the first grating 104a and the third grating 104c. The first in-coupled light $P1_1$ that is on the first incident path P1 is first in-coupled by the first grating 104a and diffracted (directed) to the edge 105. The edge 105 absorbs a first portion of the first in-coupled light $P1_1$. The first edge-reflected light $P1_2$ (the second portion of the first in-coupled light $P1_1$) reflects off the angled portion 402 and is directed to the third grating 104c according to the second re-direction angle θ_2. However, due to the second re-direction angle θ_2, the first edge-reflected light $P1_2$ is directed (diffracted) to another portion of the edge 105 by the third grating 104c. The first edge-reflected light $P1_2$ undergoes an additional interaction with the black coating of the edge 105 of the substrate 101. The first edge-reflected light $P1_2$ is not out-coupled to the user because it is absorbed by the edge 105 due to the additional interaction. Therefore, due to the angled portion 402 the first edge-reflected light $P1_1$ does not out-couple to the field of view of the user. The first edge-reflected light $P1_2$ remains in TIR with the substrate 101 after getting diffracted by the third grating 104c.

[0036] In some embodiments, the second re-direction angle θ_2 may be determined based on the first grating period Λ_{IC}, the second grating period Λ_{OC}, the first grating angle θ_{IC}, and the second grating angle θ_{OC}. In some embodiments, the second re-direction angle θ_2 may be determined using an inequality (Eq.1):

$$\left(\frac{\lambda}{\Lambda_{IC}}\right)^2 + \left(\frac{\lambda}{\Lambda_{OC}}\right)^2 + 2\frac{\lambda}{\Lambda_{IC}}\frac{\lambda}{\Lambda_{OC}}cos(2\theta_{die} - \theta_{IC} - \theta_{OC}) > 1 \quad \text{(Eq. 1)}$$

[0037] where λ is the wavelength of light, Λ_{IC} is the first grating period, Λ_{OC} is the second grating period, θ_{IC} is the first grating angle, and θ_{OC} is the second grating angle. Because Eq. 1 is an inequality, it is understood that more than one the second re-direction angle $\theta_{2\ can}$ satisfy Eq. 1. In some embodiments, the second re-direction angle θ_2 may be selected based on the best fit of the desired shape of the waveguide 400. Advantageously, the incident light of each incident light path can be prevented from coupling to the center of the field of view of the user by adjusting the grating angles, the grating periods, and/or the shape of the edge 105.

[0038] Although FIG. 4A includes one angled portion 402 used to re-direct a single light path, this is for example purposes only. It is understood that the edge 105 of the substrate 101 of waveguide 400 can include multiple angled portions that cause

incident light of other incident paths to avoid coupling to the center of the field of view of the user. For example, the edge 105 of the substrate 101 of waveguide 400 can include an angled portion along the second incident path P2 that causes the second edge-reflected light $P2_2$ to be diffracted by the third grating 104c and remain in TIR.

[0039] FIG. 4B illustrates a k-space plot of a waveguide having the arrangement shown in FIG. 4A according to one or more embodiments. The sequence of incident light in-coupling with the waveguide 400, reflecting off the angled portion 402, and at least partially avoiding out-coupling with the center of the field of view of the user is represented by k-space diagram 450. The k-space diagram 450 schematically represents the waveguide 400 by an outer circle 452 and the material surrounding the waveguide 400 (e.g., air or another optical element) is represented by inner circle 454. The inner circle 454 represents conditions for light to propagate in air. The outer circle 452 corresponds to the angle condition for light to propagate within the substrate 101. The center of the field of view of the user is represented by field of view (FOV) circle 453. The annulus between the concentric inner circle 454 and outer circle 452 corresponds to the TIR condition for light to propagate in the waveguide 400.

[0040] As illustrated in FIG. 4B, in operation, white incident light, such as the first in-coupled light $P1_1$ is in-coupled by the first grating 104a and undergoes total-internal-reflection (TIR) through the waveguide 400 to the edge 105. The incident light propagates internally within the waveguide 400 to the edge 105 of the substrate 101 as represented by a vector 460a extending from the inner circle 354 to the outer circle 352. A blue channel light (wavelengths of 380 nm to about 495 nm), a green channel light (wavelength of about 495 nm to about 590 nm), a red channel light (wavelength of about 590 nm to about 750 nm) propagate under total internal reflection (TIR) at different decay rates.

[0041] As shown in Figure 4B, at a first TIR state 457 the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV c1, a green FOV c2, and a red FOV c3 offset from each other.

[0042] A portion of the beams of the light channels are absorbed by the black coating of the edge 105 and a portion of the beams of the light channels reflects off the edge 105 (i.e., the first edge-reflected light $P1_2$). The portion of the reflected

beams of the light channels are as represented by a vector 460b extending from the inner circle 354 to the outer circle 352. Due to the angled portion 402, as shown in Figure 4B, at a second TIR state 467 the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV c1, a green FOV c2, and a red FOV c3 offset from each other. The portion of the reflected beams of the light channels propagate to and are diffracted by the third grating 104c and remains in the outer circle 452 (i.e., in total internal reflection of the waveguide 400). Thus, none of the first edge-reflected light $P1_2$ is out-coupled to the center of the field of view of the user. The portion of the reflected beams of the light channels that are diffracted by the third grating 104c are represented by vector 460c. Due to the diffraction of the third grating 104c, at a third TIR state 469, the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV c1, a green FOV c2, and a red FOV c3 offset from each other. Stated differently, due to the angled portion 402, the first edge-reflected light $P1_2$ remains in the outer circle 452 (i.e., in total internal reflection of the waveguide 400).

[0043] In some embodiments, the edge 105 of the substrate 101 can be shaped to avoid coupling of incident light of the entire field of view for the entire field of view of the user. FIG. 5A is a perspective, frontal view of a waveguide 500 used to prevent incident light from coupling with the entire field of view of a user according to one or more embodiments. FIG. 5B illustrates a k-space plot of a waveguide having the arrangement shown in FIG. 5A according to one or more embodiments. In one or more embodiments, there are multiple paths of undesired incident light in the entire field of view of the virtual image that are in-coupled via the first grating 104a. For example, as illustrated in FIG. 5A, in-coupled light on an incident path of light of the entire field of view of the displayed image includes a path of blue incident light 502a of a blue field of view (FOV) r1 (FIG. 5B), a path of green incident light 502b of a green FOV r2 (FIG. 5B), and path of red incident light 502c of a red FOV r3 (FIG. 5B). The line of the path of blue incident light 502a denotes the centroid of the blue FOV r1. The line of the path of green incident light 502b denotes the centroid of the green FOV r2. The line of the path of red incident light 502c denotes the centroid of the red FOV r3. Although one incident path of the entire field of view of the virtual image is shown this is for example purposes only.

[0044] In some embodiments, to redirect the light of all three incident paths 502a-502c the edge 105 of the substrate 101 includes a curved portion 504. The curved portion 504 is shaped to have an angle of curvature θ_c positioned on each of the incident paths 502a-502c. The angle of curvature θ_c may be defined as the angle between the horizontal axis 108 and the tangent line 508 to the curved portion 504. The angle of curvature θ_c have any angle of about 0 and about 360° and is determined based on the geometry and layout of the first grating 104a and the third grating 104c.

[0045] In-coupled light of each of the incident paths 502a-502c are in-coupled and diffracted by the first grating 104a towards the curved portion 504. For example, blue in-coupled light $502a_1$ of the path of blue incident light 502a is diffracted towards the curved portion 504. Green in-coupled light $502b_1$ of the path of green incident light 502b is diffracted towards the curved portion 504. Red in-coupled light $502c_1$ of the path of red incident light 502c is diffracted towards the curved portion 504. A first portion of each in-coupled light is absorbed by the black coating of the edge 105. A first portion of the blue in-coupled light $502a_1$ is absorbed by the edge 105. A first portion of the green in-coupled light $502b_1$ is absorbed by the edge 105. A first portion of the red in-coupled light $502c_1$ is absorbed by the edge 105 A second portion of each in-coupled light is reflected (i.e., edge-reflected light) off the curved portion 504 and towards the third grating 104c according to the angle of curvature θ_c. Blue edge-reflected light $502a_2$, a green edge-reflected light $502b_2$, and red edge-reflected light $502c_2$ are all directed to the third grating 104c according to the angle of curvature θ_c. The third grating 104c diffracts the blue edge-reflected light $502a_2$, green edge-reflected light $502b_2$, and red edge-reflected light $502c_2$. The blue edge-reflected light $502a_2$, green edge-reflected light $502b_2$, and red edge-reflected light $502c_2$ remain in TIR and are not out-coupled. In one embodiment, the blue edge-reflected light $502a_2$, green edge-reflected light $502b_2$, and red edge-reflected light $502c_2$ are diffracted by the third grating to another portion of the edge 105. Thus causing the blue edge-reflected light $502a_2$, green edge-reflected light $502b_2$, and red edge-reflected light $502c_2$ to have an additional interaction with the edge 105. The additional interaction with the edge causes the blue edge-reflected light $502a_2$, green edge-reflected light $502b_2$, and red edge-reflected light $502c_2$ to be absorbed.

[0046] Although FIG. 5A includes one curved portion, this is for example purposes only. It is understood that the edge of the substrate 101 of waveguide 500 can include

multiple curved portions to prevent edge-reflected light from out-coupling to the entire field of view of the user.

[0047] As illustrated in FIG. 5B, the sequence of incident light in-coupling with the waveguide 500, reflecting off the curved portion 504, and at least partially avoiding out-coupling with the entire field of view of the user is represented by k-space diagram 550. The k-space diagram 550 schematically represents the waveguide 500 by an outer circle 552 and the material surrounding the waveguide 500 (e.g., air or another optical element) is represented by inner circle 554. The inner circle 554 represents conditions for light to propagate in air. The outer circle 552 corresponds to the angle condition for light to propagate within the substrate 101. The field of view of the user is represented by field of view (FOV) rectangle 553. The annulus between the concentric inner circle 554 and outer circle 552 corresponds to the TIR condition for light to propagate in the waveguide 500.

[0048] As illustrated in FIG. 5B, in operation, white incident light, such as the incident light of the incident paths 502a-502c is in-coupled by the first grating 104a and undergoes total-internal-reflection (TIR) through the waveguide 500 to the edge 105. The incident light propagates internally within the waveguide 500 to the edge 105 of the substrate 101 as represented by a vector 560a extending from the inner circle 354 to the outer circle 352. A blue channel light (wavelengths of 380 nm to about 495 nm), a green channel light (wavelength of about 495 nm to about 590 nm), a red channel light (wavelength of about 590 nm to about 750 nm) propagate under total internal reflection (TIR) at different decay rates.

[0049] As shown in Figure 5B, at a first TIR state 557 the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV r1, a green FOV r2, and a red FOV r3 offset from each other.

[0050] A portion of the beams of the light channels are absorbed by the black coating of the edge 105 and a portion of the beams of the light channels reflects off the edge 105 (i.e., the blue edge-reflected light $502a_2$, green edge-reflected light $502b_2$, and red edge-reflected light $502c_2$). The portion of the reflected beams of the light channels are as represented by a vector 560b extending from the inner circle 554 to the outer circle 552. Due to the curved portion 504, as shown in Figure 5B, at a

second TIR state 567 the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV r1, a green FOV r2, and a red FOV r3 offset from each other.

[0051] The reflected portion of the reflected beams of the light channels propagate to and are diffracted by the third grating 104c and remains in the outer circle 552 (i.e., in total internal reflection of the waveguide 500). Thus, none of the incident light is out-coupled to the field of view of the user. The reflected portion of the reflected beams of the light channels that are diffracted by the third grating 104c are represented by vector 560c. Due to the diffraction of the third grating 104c at a third TIR state 569, the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV r1, a green FOV r2, and a red FOV r3 offset from each other. Stated differently, due to the curved portion 504, the diffracted incident remains in the outer circle 552 (i.e., in total internal reflection of the waveguide 500). Thus, the entire field of in-coupled incident light remains in TIR and is not out-coupled to the field of view of the user.

What is claimed is:

1. A waveguide comprising:

a waveguide substrate, the waveguide substrate having a first surface and a second surface opposing the first surface, the first and second surfaces are connected by an edge, the edge having an angled portion with a re-direction angle; and

an in-coupler grating disposed over the first surface or the second surface, wherein the in-coupler grating is operable to diffract in-coupled light on a first incident path to the angled portion of the edge that absorbs a first portion of the in-coupled light and directs a second portion of in-coupled light to another portion of the edge at least partially avoiding an out-coupler grating according to the re-direction angle.

2. The waveguide of claim 1, wherein the in-coupler grating has a grating period of about 250 to about 500 nm.

3. The waveguide of claim 1, wherein the out-coupler grating has a grating period of about 250 to about 500 nm.

4. The waveguide of claim 1, wherein the waveguide substrate comprises at least one of: glass, silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), fused silica, quartz, sapphire (Al_2O_3), silicon carbide (SiC), lithium niobate ($LiNbO_3$), or indium tin oxide (ITO).

5. The waveguide of claim 1, wherein the waveguide substrate comprises glass that comprises greater than 2 percent by weight of lanthanide (Ln), titanium (Ti), tantalum (Ta), or combinations thereof.

6. The waveguide of claim 1, wherein the in-coupler grating and the out-coupler grating comprise structures comprising a grating material comprising at least one of: silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate (Cd_2SnO_4), or silicon carbon-nitride (SiCN) containing materials.

7. A waveguide comprising:

a waveguide substrate, the waveguide substrate having a first surface and a second surface opposing the first surface, the first and second surfaces are connected by an edge, the edge having an angled portion with a re-direction angle;

an in-coupler grating disposed over the first surface or the second surface, wherein the in-coupler grating is operable to diffract in-coupled light on a first incident path to the angled portion of the edge that absorbs a first portion of the in-coupled light and directs a second portion of in-coupled light to an out-coupler grating according to the re-direction angle of the angled portion; and

the out-coupler grating, wherein the out-coupler grating diffracts the second portion to remain under total internal reflection (TIR) within the waveguide substrate.

8. The waveguide of claim 7, wherein the in-coupler grating has a grating period of about 250 to about 500nm.

9. The waveguide of claim 7, wherein the out-coupler grating has a grating period of about 250 to about 500 nm.

10. The waveguide of claim 7, wherein the waveguide substrate comprises at least one of: glass, silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), fused silica, quartz, sapphire (Al_2O_3), silicon carbide (SiC), lithium niobate ($LiNbO_3$), or indium tin oxide (ITO).

11. The waveguide of claim 7, wherein the waveguide substrate comprises glass that comprises greater than 2 percent by weight of lanthanide (Ln), titanium (Ti), tantalum (Ta), or combinations thereof

12. The waveguide of claim 7, wherein the in-coupler grating and the out-coupler grating comprise structures comprising a grating material comprising at least one of: silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5),

silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate (Cd_2SnO_4), or silicon carbon-nitride (SiCN) containing materials.

13. The waveguide of claim 7, wherein the re-direction angle is determining by solving

$$\left(\frac{\lambda}{\Lambda_{IC}}\right)^2 + \left(\frac{\lambda}{\Lambda_{OC}}\right)^2 + 2\frac{\lambda}{\Lambda_{IC}}\frac{\lambda}{\Lambda_{OC}}cos(2\theta_{die} - \theta_{IC} - \theta_{OC}) > 1$$

wherein where λ corresponds to a wavelength of light, Λ_{IC} corresponds to a grating period of the in-coupler grating, Λ_{OC} corresponds to a grating period of the out-coupler grating, θ_{IC} corresponds to a grating angle of the in-coupler grating, θ_{OC} corresponds to a grating angle of the out-coupler grating, and θ_2 corresponds to the re-direction angle.

14. A waveguide comprising:

a waveguide substrate, the waveguide substrate having a first surface and a second surface opposing the first surface, the first and second surface are connected by an edge, the edge having an curved portion with an angle of curvature;

an in-coupler grating disposed over the first surface or the second surface, wherein:

the in-coupler grating is operable to diffract in-coupled light on a first incident path to the curved portion, the in-coupled light having a red field of view (FOV), a green FOV, and a blue FOV; and

the curved portion absorbs a first portion of the red FOV, the green FOV, and the blue FOV, and directs a second portion of the red FOV, the green FOV, and the blue FOV to an out-coupler grating according to the angle of curvature of the curved portion; and

the out-coupler grating, wherein the out-coupler grating diffracts the second portion to remain under total internal reflection (TIR) within the waveguide substrate.

15. The waveguide of claim 14, wherein the waveguide substrate comprises at least one of: glass, silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride

(GaN), fused silica, quartz, sapphire (Al_2O_3), silicon carbide (SiC), lithium niobate ($LiNbO_3$), or indium tin oxide (ITO).

16. The waveguide of claim 14, wherein the waveguide substrate comprises greater than 2 percent by weight of lanthanide (Ln), titanium (Ti), tantalum (Ta), or combinations thereof

17. The waveguide of claim 14, wherein the in-coupler grating and the out-coupler grating comprise structures comprising a grating material comprising at least one of: silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate (Cd_2SnO_4), or silicon carbon-nitride (SiCN) containing materials.

18. The waveguide of claim 14, wherein the in-coupler grating has a grating period of about 250 to about 500 nm.

19. The waveguide of claim 14, wherein and the out-coupler grating has a grating period of about 250 to about 500 nm.

20. The waveguide of claim 14, further comprising a pupil expansion grating.