

MULTI-MATERIAL GRATINGS WITH INCREASED TRANSMISSION AND REDUCED REFLECTION

BACKGROUND

Field

[0001] Embodiments of the present disclosure generally relate to augmented reality displays. More specifically, the disclosure relates to gratings of waveguide combiners for augmented reality displays.

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 three-dimensionally generated 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 enhance or augment the environment that the user experiences. Image sharpness of the virtual image may be affected by the environment.

[0004] Further, HMDs frequently employ materials characterized by high refractive indices. While advantageous for optical properties, these materials introduce low transmission and high reflection. These characteristics can negatively impact the aesthetics of HMDs, makes it more difficult to see the user's eyes from the outside of the headset, and can cause distracting stray reflections within the user's field of view.

[0005] Accordingly, there is a need for an improved waveguide combiner that minimizes reflection while maintaining functionality.

SUMMARY

[0006] Embodiments of the present disclosure generally relate to augmented reality displays. More specifically, the disclosure relates to gratings of waveguide combiners for augmented reality displays with grating structures including a multi-material layer stack to reduce reflections off of the grating structures.

[0007] In an embodiment, a waveguide combiner is provided. The waveguide combiner includes a substrate having a substrate refractive index, and a grating having a plurality of grating structures. Each grating structure of the plurality of grating structures includes a multi-material layer stack. The multi-material layer stack has a first layer disposed over a surface of the substrate, where the first layer has a first refractive index. A second layer is disposed on the first layer having a second refractive index less than the first refractive index. A third layer is disposed on the second layer having a third refractive index less than the second refractive index.

[0008] In another embodiment, a waveguide combiner is provided. The waveguide combiner includes a substrate having a substrate refractive index. A first layer of material is disposed over the substrate having a first refractive index. The waveguide combiner also includes a grating having a plurality of structures, each grating structure of the plurality of structures including a multi-material layer stack. The multi-material layer stack has a second layer disposed on the first layer, the second layer having a second refractive index less than the first refractive index, and a third layer disposed on the second layer, the third layer having a third refractive index less than the second refractive index.

[0009] In yet another embodiment, a waveguide combiner is provided. The waveguide combiner includes a substrate having a substrate refractive index, and an input coupling grating and an output coupling grating, the input coupling grating and the output coupling grating including a plurality of structures. Each grating structure of the plurality of structures includes a multi-material layer stack. The multi-material layer stack has a first layer disposed over a surface of the substrate having a first refractive index, a second layer disposed on the first layer, the second layer having a second refractive index less than the first refractive index, and a third layer disposed on the second layer, the third layer having a third refractive index less than the second refractive index.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] 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.

[0011] Figure 1 shows a perspective, frontal view of a waveguide combiner, according to certain embodiments.

[0012] Figure 2A illustrates a schematic, cross-sectional view of a portion of a grating, according to certain embodiments.

[0013] Figure 2B illustrates a schematic, cross-sectional view of a portion of a grating, according to certain embodiments.

[0014] Figure 2C illustrates a schematic, cross-sectional view of a portion of a grating, according to certain embodiments.

[0015] Figure 3 illustrates a cross-sectional view of a portion of a waveguide combiner, according to certain embodiments.

[0016] 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

[0017] Embodiments of the present disclosure generally relate to augmented reality displays. More specifically, the disclosure relates to gratings of waveguide combiners for augmented reality displays with grating structures including a multi-material layer stack to reduce reflections off of the grating structures.

[0018] Figure 1 is a perspective, frontal view of a waveguide combiner 100. It is to be understood that the waveguide combiner 100 described below is an exemplary

waveguide combiner. The waveguide combiner 100 includes an input coupling grating 102 defined by a plurality of grating structures 108, a pupil expansion grating 104 defined by a plurality of grating structures 110, and an output coupling grating 106 defined by a plurality of grating structures 112. The input coupling grating 102 receives incident beams of light (a virtual image) having an intensity from a microdisplay. The incident beams are incoupled by the input coupling grating 102 and undergo total-internal-reflection (TIR) through the waveguide combiner 100 until the beams contact the plurality of grating structures 110 in the pupil expansion grating 104.

[0019] The beams contact a grating of the plurality of grating structures 110 of the pupil expansion grating 104. A portion of the beams undergo TIR in the pupil expansion grating 104 until the T1 beams contact another grating of the plurality of grating structures 110, and another portion of the beams are coupled through the waveguide combiner 100 to the output coupling grating 106. The portion of the beams that undergo TIR in the pupil expansion grating 104 continue to contact gratings of the plurality of grating structures 110 until either the intensity of the beams coupled through the waveguide combiner 100 to the pupil expansion grating 104 is depleted, or the remaining beams propagating through the pupil expansion grating 104 reach the end of the pupil expansion grating 104.

[0020] The beams pass through the waveguide combiner 100 to the output coupling grating 106 and undergo TIR in the waveguide combiner 100 until the beams contact a grating of the plurality of grating structures 112 where the beams are split into beams that undergo TIR in the output coupling grating 106 until the T1 beams contact another grating of the plurality of grating structures 112, or beams that pass out of the waveguide combiner 100 (i.e., beams that are outcoupled). The beams that undergo TIR in the output coupling grating 106 continue to contact gratings of the plurality of grating structures 112 until either the intensity of the beams pass through the waveguide combiner 100 to the output coupling grating 106 is depleted, or the remaining beams propagating through the output coupling grating 106 have reached the end of the output coupling grating 106. The output coupling grating beams outcoupled out of the waveguide combiner 100 result in a field of view of the virtual image produced from the microdisplay that is projected to the from the user's perspective such that the user can view the virtual image.

[0021] In order to propagate in TIR, the light must travel in a material of index of refraction above a certain threshold, determined by the component of the k-vector parallel to the waveguide plane $k_{||}$ and the free-space wavelength of the light λ_0 :

$$n_{\text{minimum}} = |k_{||} * \lambda_0 / 2\pi|$$

[0022] Gratings comprised of materials with refractive index lower than this requirement cannot as effectively diffract light propagating in TIR. Thus, to uniformly diffract light of across a wide range of different angles and wavelengths with in TIR (as is required in AR waveguide combiner devices), it is desirable to have gratings (such as the input coupling gratings, pupil expansion gratings, or the output coupling gratings) with grating structures 108, 110, and 112 having a grating refractive index greater than a substrate refractive index. Optical transmission and reflection across a material interface are directly related to the difference in refractive indices between the two materials. Reflectivity at normal incidence across a boundary between materials with different refractive indices is governed by the Fresnel equation, shown below, where the reflectivity, R, between a first material having an index of refraction n_1 and a second material having an index of refraction n_2 is given by:

$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$

[0023] High refractive index materials and structures inherently exhibit elevated reflection, a phenomenon that holds true for thin films and gratings. The reflection caused by the difference between the grating refractive index and the substrate refractive index can induce TIR results in the glare. When waveguide combiners are used as lenses in AR displays, such as glasses, the glare produced by the high refractive index of the materials used obscures the user's eyes, which is not aesthetically desirable.

[0024] Thus, the waveguide combiners described herein include gratings with structures of a multi-material layer stack disposed over a substrate where a first layer of the multi-material layer stack includes a first layer with a first index of refraction that is higher than the index of refraction of the substrate. Subsequent layers in the multi-material layer stack disposed over the first layer have progressively decreasing indices of refraction.

[0025] Figure 2A illustrates a schematic, cross-sectional view of a portion 200A of a grating arrangement. At least one of the input coupling grating 102, the pupil expansion grating 104, or the output coupling grating 106 includes the grating arrangement described herein. In an embodiment, the grating structures 110 are disposed over a substrate 202.

[0026] In some embodiments, which may be combined with other embodiments described herein, the material of the grating structures 110 of the input coupling grating 102, the pupil expansion grating 104, and the output coupling grating 106 may differ. For example, it is desirable to match the reflection and transmission of the input coupling grating 102, the pupil expansion grating 104 and the output coupling grating 106 to a waveguide region (not shown) in the substrate 202 between the gratings, so that the waveguide combiner 100 is aesthetically appealing as light is not reflected to the outside environment. In other words, there is no eye glow of a projected image visible on the non-user side of the device. Thus, if one of the gratings, e.g., the output coupling grating 106, includes a single material that has low reflection relative to the waveguide region, the grating structures 110 of the output coupling grating 106 need only include the single material rather than include a multi-material layer stack 204. Similarly, if the input coupling grating 102 includes a single material has a low reflection relative to the waveguide region, having a multi-material layer stack 204 may not be needed and the grating structures 110 may include only the single material. Additionally, in other embodiments, each of the multi-material layer stack 204 of the input coupling grating 102, the pupil expansion grating 104, and the output coupling grating 106 may include the same layer materials across each multi-material layer stack 204, different combinations of materials for each layer of each multi-material layer stack 204, or a combination thereof. For example, the multi-material layer stack 204 of the input coupling grating 102 may include TiOx, SiN, and AlOx layers, the multi-material layer stack 204 of the pupil expansion grating 104 may include SiC, SiN, AlOx, and SiOx layers, and the multi-material layer stack 204 of the output coupling grating 106 may include diamond, TiOx, NbOx, and ITO layers.

[0027] The substrate 202 may be formed from any suitable material, provided that the substrate 202 can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the waveguide combiner 100 described herein. Substrate selection may include optical device 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 202 includes an optically transparent material. In one embodiment, which may be combined with other embodiments described herein, the substrate 202 is transparent with absorption coefficient smaller than 0.001. Suitable examples may include silicon (Si), silicon dioxide (SiO₂), fused silica, quartz, silicon carbide (SiC), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), sapphire, or combinations thereof. In another embodiment, which may be combined with other embodiments described herein, the substrate 202 has a refractive index of about 1.5 to about 2.6. The substrate 202 having a refractive index greater than about 1.8 includes, but is not limited to, lithium tantalate (LiTaO₃), lithium niobate (LiNbO₃), SiC, or combinations thereof.

[0028] As shown in Figure 2A, each of the grating structures 110 may be binary structures with a top surface substantially parallel with a top surface 202A of the substrate 202. The grating structures 110 may each include a multi-material layer stack 204. The multi-material layer stack 204 includes a plurality of layers 204a extending away from the substrate 202 and stacked along a vertical grating axis 206a that is substantially perpendicular to the major axis or the top surface 202A of the substrate 202. As shown in Figure 2A, the plurality of layers 204a of the multi-material layer stack 204 includes a first layer 208, a second layer 210, a third layer 212, and a fourth layer 214. Although shown, each of the third layer 212 and the fourth layer 214 are optional, e.g., the multi-material stack 204 may include only the first layer 208 and the second layer 210. Alternatively, the multi-material stack 204 may include additional layers, such as a fifth layer (not shown) or sixth layer (not shown). Each of the first layer 208, the second layer 210, the third layer 212, and the fourth layer 214 in each of the multi-material layer stack 204 may include at least one different material with a different refractive index. The at least one different material includes, but is not limited to, titanium oxide (TiO_x), silicon nitride (SiN), silicon oxide (SiO_x), niobium oxide (NbO_x), silicon carbide (SiC), aluminum oxide (AlO_x), indium tin oxide (ITO), diamond, or combinations thereof. For example, the multi-material layer stack 204 may have the first layer 208 include TiO_x with a refractive index of about 2.3 to about

2.6, the second layer 210 include SiN with a refractive index of about 2.0, third layer 212 may include AlOx with a refractive index of about 1.7, and the fourth layer 214 include SiOx, with a refractive index of about 1.4.

[0029] In the embodiment shown in Figure 2A, the first layer 208 includes a first refractive index, the second layer 210 includes a second refractive index, the third layer 212 includes a third refractive index, and the fourth layer 214 includes a fourth refractive index. The first refractive index is greater than the second refractive index, the third refractive index, and the fourth refractive index. The second refractive index is greater than the third refractive index and the fourth refractive index. The third refractive index is greater than the fourth refractive index. For example, the first refractive index is about 2.0 and about 2.5, such as about 2.3. The second refractive index is about 1.9 and 2.3, such as about 2.0. The third refractive index is about 1.5 to about 1.9, such as about 1.7. The fourth refractive index is about 1.3 to about 1.7, such as about 1.5. The difference in refractive index between each adjacent layer may be at least about 0.05, to about 0.5, such as about 0.05 to about 0.2.

[0030] The first layer 208 having the greatest refractive index interacts with the light in TIR within the substrate 202, while allowing the second layer 210, the third layer 212, and the fourth layer 214 with a progressively lower indices of refraction to act as an anti-reflective coating to reduce reflection from the surface of the pupil expansion grating 104. Without being bound by theory, it is believed the progression of refractive index improves the aesthetic of the waveguide combiner 100. The geometry of the grating structures 110 may be any desired geometry. In some embodiments, each of the first layer 208, the second layer 210, the third layer 212, and the fourth layer 214 may have a thickness of between 0.5 nm to about 2 μm . In such embodiments, the resulting total grating thickness 216 may be between about 1 nm to about 20 μm , such as between about 1 nm and 10 μm .

[0031] Figure 2B shows a schematic, cross-sectional view of a portion 200B of a grating arrangement. At least one of the input coupling grating 102, the pupil expansion grating 104, or the output coupling grating 106 includes the grating arrangement described herein.

[0032] In some embodiments, which may be combined with other embodiments described herein, the material of the grating structures 110 of the input coupling

grating 102, the pupil expansion grating 104, and the output coupling grating 106 may differ. For example, it is desirable to match the reflection and transmission of the input coupling grating 102, the pupil expansion grating 104 and the output coupling grating 106 to a waveguide region (not shown) in the substrate 202 between the gratings, so that the waveguide combiner 100 is aesthetically appealing as light is not reflected to the outside environment. In other words, there is no eye glow of a projected image visible on the non-user side of the device. Thus, if one of the gratings, e.g., the output coupling grating 106, includes a single material that has low reflection relative to the waveguide region, the grating structures 110 of the output coupling grating 106 need only include the single material rather than include a multi-material layer stack 204. Similarly, if the input coupling grating 102 includes a single material has a low reflection relative to the waveguide region, having a multi-material layer stack 204 may not be needed and the grating structures 110 may include only the single material. Additionally, in other embodiments, each of the multi-material layer stack 204 of the input coupling grating 102, the pupil expansion grating 104, and the output coupling grating 106 may include the same layer materials across each multi-material layer stack 204, different combinations of materials for each layer of each multi-material layer stack 204, or a combination thereof. For example, the multi-material layer stack 204 of the input coupling grating 102 of the may include TiOx, SiN, and AlOx layers, the multi-material layer stack 204 of the pupil expansion grating 104 may include SiC, SiN, AlOx, and SiOx layers, and the multi-material layer stack 204 of the output coupling grating 106 may include diamond, TiOx, NbOx, and ITO layers.

[0033] As shown in Figure 2B, each of the grating structures 110 are disposed over a substrate 202. The grating structures 110 include a multi-material layer stack 204. The multi-material layer stack 204 includes a plurality of layers 204a, e.g., the first layer 208, the second layer 210, the third layer 212, and the fourth layer 214, extending away from the substrate 202. The geometry of the grating structures 110 may be any desired geometry. In some embodiments, each of the grating structures 110 may be angled structures having sidewalls that are slanted relative to the top surface 202A of the substrate 202, e.g., the grating structures 110 are angled along an angled grating axis 206b that is at an angle relative to the major axis or THE top surface 202A of substrate 202. In some embodiments, which may be combined with other embodiments described herein, each of the first layer 208, the second layer 210,

the third layer 212, and the fourth layer 214 may have a thickness of between 0.5 nm to about 2 μm . In such embodiments, the resulting total grating thickness 216 may therefore be between about 1 nm to about 20 μm , such as between about 1 nm and 10 μm .

[0034] Each of the first layer 208, the second layer 210, the third layer 212, and the fourth layer 214 in each of the multi-material layer stack 204 may include at least one different material with a different refractive index. The at least one different material includes, but is not limited to, titanium oxide (TiOx), silicon nitride (SiN), silicon oxide (SiOx), niobium oxide (NbOx), silicon carbide (SiC), aluminum oxide (AlOx), indium tin oxide (ITO), diamond, or combinations thereof.

[0035] In the embodiment shown in Figure 2B, the first layer 208 includes a first refractive index, the second layer 210 includes a second refractive index, the third layer 212 includes a third refractive index, and the fourth layer 214 includes a fourth refractive index. The first refractive index is greater than the second refractive index, the third refractive index, and the fourth refractive index. The second refractive index is greater than the third refractive index and the fourth refractive index. The third refractive index is greater than the fourth refractive index. For example, the first refractive index may be between about 2.0 and about 2.5, such as about 2.3, and the second refractive index may be between about 1.9 and 2.3, such as 2.0, the third refractive index is about 1.5 to about 1.9, such as about 1.7, and the fourth refractive index is about 1.3 to about 1.7, such as about 1.5. The difference in refractive index between each adjacent layer is least about 0.05 to about 0.5, such as about 0.05 to about 0.2.

[0036] The first layer 208 having the greatest refractive index interacts with the substrate 202 to allow for TIR within the substrate 202 replacing the need for a high-refractive index thin film to be disposed below the grating structures 110, while allowing the second layer 210, the third layer 212, and the fourth layer 214 with a progressively lower indices of refraction to act as an anti-reflective coating to reduce reflection from the surface of the pupil expansion grating 104. The progression of refractive indices improves the aesthetic of the waveguide combiner 100.

[0037] Figure 2C illustrates a schematic, cross-sectional view of a portion 200C of a grating arrangement. At least one of the input coupling grating, the pupil expansion

grating 104, or the output coupling grating 106 includes the grating arrangement described herein.

[0038] In some embodiments, which may be combined with other embodiments described herein, the material of the grating structures 110 of the input coupling grating 102, the pupil expansion grating 104, and the output coupling grating 106 may differ. For example, it is desirable to match the reflection and transmission of the input coupling grating 102, the pupil expansion grating 104 and the output coupling grating 106 to a waveguide region (not shown) in the substrate 202 between the gratings, so that the waveguide combiner 100 is aesthetically appealing as light is not reflected to the outside environment. In other words, there is no eye glow of a projected image visible on the non-user side of the device. Thus, if one of the gratings, e.g., the output coupling grating 106, includes a single material that has low reflection relative to the waveguide region, the grating structures 110 of the output coupling grating 106 need only include the single material rather than include a multi-material layer stack 204. Similarly, if the input coupling grating 102 includes a single material has a low reflection relative to the waveguide region, having a multi-material layer stack 204 may not be needed and the grating structures 110 may include only the single material. Additionally, in other embodiments, each of the multi-material layer stack 204 of the input coupling grating 102, the pupil expansion grating 104, and the output coupling grating 106 may include the same layer materials across each multi-material layer stack 204, different combinations of materials for each layer of each multi-material layer stack 204, or a combination thereof. For example, the multi-material layer stack 204 of the input coupling grating 102 of the may include TiOx, SiN, and AlOx layers, the multi-material layer stack 204 of the pupil expansion grating 104 may include SiC, SiN, AlOx, and SiOx layers, and the multi-material layer stack 204 of the output coupling grating 106 may include diamond, TiOx, NbOx, and ITO layers.

[0039] The grating structures 110 are disposed over a substrate 202. In some embodiments, which may be combined with other embodiments described herein, each of the grating structures 110 may be binary structures such that each of the grating structures 110 has sidewalls that are substantially perpendicular to the surface 202A of the substrate 202. Alternatively, the grating structures 110 may be angled such that the grating structures 110 have angled grating axis 206b that is at an angle to the major axis of substrate 202. The grating structures 110 include a multi-material

layer stack 204 disposed over a first layer 208. The multi-material layer stack 204 includes a plurality of layers 204a, e.g., the second layer 210, the third layer 212, and the fourth layer 214, extending away from the substrate 202.

[0040] As shown in Figure 2C, the first layer 208 extends along the major axis of the substrate 202 and covers the surface 202A such that the surface 202A is not exposed. The second layer 210 is then disposed over the first layer 208 and covers a first layer top surface 208A of the first layer 208. The second layer 210 may be partially etched, such that a residual portion 210a of the second layer 210 is between each grating structure 210b of the second layer. The residual portion 210a is planar along the first layer 208. Alternatively, the second layer 210 may be etched such that there is no residual portion 210a between the grating structures 210b, partially exposing the first layer top surface 208A of first layer 208. The third layer 212 and the fourth layer 214 are then disposed onto the grating structures 210b of the second layer 210. In some embodiments, the third layer 212 and fourth layer 214 each have a width equal to the grating structures 210b of the second layer 210. In some embodiments, each of the first layer 208, the second layer 210, the third layer 212, and the fourth layer 214 has a thickness of between 0.5 nm to about 2 μm . In such embodiments, the resulting total grating thickness 216 may therefore be between about 1 nm to about 20 μm , such as between about 1 nm and 10 μm .

[0041] In some embodiments, which may be combined with other embodiments described herein, each of the first layer 208, the second layer 210, the third layer 212, and the fourth layer 214 in each of the multi-material layer stack 204 may include at least one different material with a different refractive. The at least one different material includes, but is not limited to, titanium oxide (TiOx), silicon nitride (SiN), silicon oxide (SiOx), niobium oxide (NbOx), silicon carbide (SiC), aluminum oxide (AlOx), indium tin oxide (ITO), diamond, or combinations thereof.

[0042] In the embodiment shown in Figure 2C, the first layer 208 includes a first refractive index, the second layer 210 includes a second refractive index, the third layer 212 includes a third refractive index, and the fourth layer 214 includes a fourth refractive index. The first refractive index is greater than the second refractive index, the third refractive index, and the fourth refractive index. The second refractive index is greater than the third refractive index and the fourth refractive index. The third

refractive index is greater than the fourth refractive index. For example, the first refractive index may be between about 2.0 and about 2.5, such as about 2.3, and the second refractive index may be between about 1.9 and 2.3, such as about 2.0. The third refractive index is about 1.5 to about 1.9, such as about 1.7. The fourth refractive index is about 1.3 to about 1.7, such as about 1.5. The difference in refractive index between each adjacent layer may be at least about 0.05, to about 0.5, such as about 0.05 to about 0.2.

[0043] The first layer 208 having the greatest refractive index interacts with the substrate 202 to allow for TIR within the substrate 202, while allowing the second layer 210, third layer 212, and the fourth layer 214 with lower indices of refraction to act as an anti-reflective coating to reduce reflection from the surface of the pupil expansion grating 104. The progression of refractive indices improves the aesthetic of the waveguide combiner 100.

[0044] Figure 3 illustrates a cross-sectional view of a portion 300 along section line 3-3 of the waveguide combiner 100 in Figure 1, according to certain embodiments. In some embodiments, the input coupling grating 102, pupil expansion grating 104, and output coupling grating 106 may be disposed over the substrate 302. The substrate 302 may include the materials discussed regarding the substrate 202 above. In some embodiments, which may be combined with other embodiments described herein, each of the input coupling grating 102, the pupil expansion grating 104, and the output coupling grating 106 may have grating structures, e.g., a first plurality of grating structures 110A, a second plurality of grating structures 110B, and a third plurality of grating structures 110C, respectively. The first plurality of grating structures 110A, the second plurality of grating structures 110B, and the third plurality of grating structures 110C each differ and illustrate one possible combination of the grating structure arrangements described in Figures 2A-2C that may be used in the waveguide combiner 100.

[0045] As shown in Figure 3, in some embodiments, each grating structure of the first plurality of grating structures 110A of the input coupling grating 102 may include only three layers, e.g., a first multi-material layer stack 304A with a first input coupling layer 308a, a second input coupling layer 310a, and a third input coupling layer 312a. The first multi-material layer stack 304A may be binary such that each of the first

plurality of grating structures 110A has sidewalls that are substantially perpendicular to a top surface 302A of the substrate 302. The first input coupling layer 308a, the second input coupling layer 310a, and the third input coupling layer 312a, extend away from the substrate 302 and are stacked along a vertical grating axis 306a that is substantially perpendicular to the major axis of substrate 302.

[0046] In some embodiments, which may be combined with other embodiments described herein, each of the first input coupling layer 308a, the second input coupling layer 310a, and the third input coupling layer 312a include at least one different material with a different refractive index. The at least one different material includes, but is not limited to, titanium oxide (TiOx), silicon nitride (SiN), silicon oxide (SiOx), niobium oxide (NbOx), silicon carbide (SiC), aluminum oxide (AlOx), indium tin oxide (ITO), diamond, or combinations thereof. For example, the first multi-material layer stack 304A may have the first input coupling layer 308a include TiOx with a refractive index of about 2.3 to about 2.6, the second input coupling layer 310a include SiN with a refractive index of about 2.0, and the third input coupling layer 312a may include AlOx with a refractive index of about 1.7.

[0047] Although the first plurality of grating structures 110A of the input coupling grating 102 is described as including the grating arrangement of the first multi-material layer stack 304A, any of the input coupling grating 102, the pupil expansion grating 104, the output coupling grating 106, or a combination thereof may include the first multi-material layer stack 304A described herein.

[0048] In some embodiments, which may be combined with other embodiments described herein, each grating structure of the second plurality of grating structures 110B of the pupil expansion grating 104 includes four layers, e.g., a second multi-material layer stack 304B with a first pupil expansion layer 308b, a second pupil expansion layer 310b, a third pupil expansion layer 312b, and a fourth pupil expansion layer 314b. The second multi-material layer stack 304B may be angled having sidewalls that are slanted relative to the surface 302A of the substrate 302, e.g., the second plurality of grating structures 110B have angled grating axis 306b that is at an angle to the major axis or top surface 302A of the substrate 302.

[0049] In some embodiments, which may be combined with other embodiments described herein, each of the first pupil expansion layer 308b, the second pupil

expansion layer 310b, the third pupil expansion layer 312b, and the fourth pupil expansion layer 314b includes at least one different material with a different refractive index. The at least one different material includes, but is not limited to, titanium oxide (TiOx), silicon nitride (SiN), silicon oxide (SiOx), niobium oxide (NbOx), silicon carbide (SiC), aluminum oxide (AlOx), indium tin oxide (ITO), diamond, or combinations thereof. The materials of the second multi-material layer stack 304B may be different from materials from the first multi-material layer stack 304A. Alternatively, the materials of the second multi-material layer stack 304B may be the same materials from the first multi-material layer stack 304A. For example, second multi-material layer stack 304B may have the first pupil expansion layer 308b include TiOx with a refractive index of about 2.3 to about 2.6, the second pupil expansion layer 310b include SiN with a refractive index of about 2.0, third pupil expansion layer 312b may include AlOx with a refractive index of about 1.7, and the fourth pupil expansion layer 314b include SiOx, with a refractive index of about 1.4.

[0050] Although the second plurality of grating structures 110B of the pupil expansion grating 104 is described as including the grating arrangement of the second multi-material layer stack 304B, any of the input coupling grating 102, the pupil expansion grating 104, the output coupling grating 106, or a combination thereof may include the second multi-material layer stack 304B described herein.

[0051] In some embodiments, which may be combined with other embodiments described herein, each of the third plurality of grating structures 110C of the output coupling grating 106 include four layers, e.g., a third multi-material layer stack 304C with a first output coupling layer 308c, a second output coupling layer 310c, a third output coupling layer 312c, and a fourth output coupling layer 314c. The third multi-material layer stack 304C may be binary such that each of the third plurality of grating structures 110C has sidewalls that are substantially perpendicular to the surface of the substrate 302. The first output coupling layer 308c, the second output coupling layer 310c, the third output coupling layer 312c and the fourth output coupling layer 314c, extend away from the substrate 302 and are stacked along a vertical grating axis 306a that is substantially perpendicular to the major axis of substrate 302.

[0052] The first output coupling layer 308c acts as a high refractive index layer that supports the remaining layer of the third multi-material layer stack 304C disposed on

top of it. The first output coupling layer 308c extends along the major axis of the substrate 302 within the output coupling grating 106 and covers the surface 302A of the substrate 302 such that the surface 302A is not exposed in the output coupling grating 106. The second output coupling layer 310c is then disposed over the first output coupling layer 308c and covers a top surface of the first output coupling layer 308c. The second output coupling layer 310c may be partially etched, such that a residual portion 310c₁ of the second output coupling layer 310c is between each grating portion 310c₂ of the second output coupling layer 310c. The residual portion 310c₁ is planar along the first output coupling layer 308c. Alternatively, the second output coupling layer 310c may be etched such that there is no residual portion 310c₁ between the grating portions 310c₂, partially exposing the top surface of first output coupling layer 308c. The third output coupling layer 312c and the fourth output coupling layer 314c are then disposed onto the second pupil expansion layer 310b of the second output coupling layer 310c.

[0053] In some embodiments, which may be combined with other embodiments described herein, each of the first output coupling layer 308c, the second output coupling layer 310c, the third output coupling layer 312c, and the fourth output coupling layer 314c includes at least one different material with a different refractive index. The at least one different material includes, but is not limited to, titanium oxide (TiOx), silicon nitride (SiN), silicon oxide (SiOx), niobium oxide (NbOx), silicon carbide (SiC), aluminum oxide (AlOx), indium tin oxide (ITO), diamond, or combinations thereof. The materials of the third multi-material layer stack 304C may be different from materials from the first multi-material layer stack 304A and the second multi-material layer stack 304B. Alternatively, the materials of the third multi-material layer stack 304C may be the same materials from the first multi-material layer stack 304A or the second multi-material layer stack 304B. For example, the third multi-material layer stack 304C may have the first output coupling layer 308c include TiOx with a refractive index of about 2.3 to about 2.6, the second output coupling layer 310c include SiN with a refractive index of about 2.0, third output coupling layer 312c may include AlOx with a refractive index of about 1.7, and the fourth output coupling layer 314c include SiOx, with a refractive index of about 1.4.

[0054] Although the third plurality of grating structures 110C of the output coupling grating 106 is described as including the grating arrangement of the third multi-

material layer stack 304C, any of the input coupling grating 102, the pupil expansion grating 104, the output coupling grating 106, or a combination thereof may include the grating arrangement described herein.

[0055] Although Figure 3 illustrates each of the first plurality of grating structures 110A, the second plurality of grating structures 110B, and the third plurality of grating structures 110C having a multi-material layer stack, it is contemplated that a multi-material layer stack for each grating, e.g., the first multi-material layer stack 304A, the second multi-material layer stack 304B, or the third multi-material layer stack 304C, may not be necessary. For example, it is desirable to match the reflection and transmission of the input coupling grating 102, the pupil expansion grating 104 and the output coupling grating 106 to a waveguide region (not shown) in the substrate 302 between the gratings, so that the waveguide combiner 100 is aesthetically appealing as light is not reflected to the outside environment. In other words, there is no eye glow of a projected image visible on the non-user side of the device. Thus, if one of the gratings, e.g., the output coupling grating 106, includes a single material that has low reflection relative to the waveguide region, the grating structures 110 of the output coupling grating 106 need only include the single material rather than the third multi-material layer stack 304C. Similarly, if the input coupling grating 102 includes a single material has a low reflection relative to the waveguide region, having the first multi-material layer stack 304A may not be needed and the grating structures 110 may include only the single material. Additionally, each of the 304A, the 304B, and the 304C may include the same layer materials across each multi-material layer stack, different combinations of materials for each layer of each multi-material layer stack, or a combination thereof, e.g., only 304A and 304C have the same layer materials. For example, the 304A may include TiOx, SiN, and AlOx layers, the 304B may include SiC, SiN, AlOx, and SiOx layers, and the 304C may include diamond, TiOx, NbOx, and ITO layers.

[0056] The present disclosure provides for a waveguide combiner having gratings including a multi-material layer stack disposed over a substrate where a first layer of the multi-material layer stack includes a first refractive index that is higher than the refractive index of the substrate. Subsequent layers in the multi-material layer stack have progressively decreasing indices of refraction. The high refractive index of the first layer allows uniform and efficient diffraction of light within TIR to still occur within

the substrate and the progressively lower refractive indices reduce reflectivity of the outer or top portion of the gratings, improving the aesthetic of the waveguide combiner as a whole.

[0057] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A waveguide combiner, comprising:
 - a substrate having a substrate refractive index; and
 - a first grating comprising a first plurality of grating structures, wherein each grating structure of the first plurality of grating structures includes a first multi-material layer stack comprising:
 - a first layer disposed over a surface of the substrate, the first layer having a first refractive index;
 - a second layer disposed on the first layer, the second layer having a second refractive index less than the first refractive index; and
 - a third layer disposed on the second layer, the third layer having a third refractive index less than the second refractive index.
2. The waveguide combiner of claim 1, wherein the first multi-material layer stack further comprises a fourth layer disposed on the third layer and having a fourth refractive index less than the third refractive index.
3. The waveguide combiner of claim 2, wherein each grating structure has sidewalls substantially perpendicular to the surface of the substrate.
4. The waveguide combiner of claim 2, wherein each grating structure has sidewalls slanted relative to the surface of the substrate.
5. The waveguide combiner of claim 1, wherein the substrate refractive index is about 1.5 to about 2.6, the first refractive index is about 2.0 to about 2.5, the second refractive index is about 1.9 to about 2.3, wherein a difference between the first refractive index and the second refractive index is about 0.05 to about 0.2.
6. The waveguide combiner of claim 1, wherein the third refractive index is about 1.5 to about 1.9 and wherein a difference between the second refractive index and the third refractive index is about 0.05 to about 0.2.
7. The waveguide combiner of claim 2, wherein the third refractive index is about 1.5 to about 1.9, the fourth refractive index is between about 1.3 and about 1.7, and

wherein a difference between the third refractive index and the fourth refractive index is between about 0.05 and about 0.2.

8. The waveguide combiner of claim 1, further comprising a second grating comprising a second plurality of grating structures, wherein each grating structure of the second plurality of grating structures includes a second multi-material layer stack comprising:

- a first layer disposed over the surface of the substrate, the first layer having the first refractive index;

- a second layer disposed on the first layer, the second layer having the second refractive index less than the first refractive index;

- a third layer disposed on the second layer, the third layer having the third refractive index less than the second refractive index; and

- a fourth layer disposed on the third layer, the fourth layer having a fourth refractive index less than the third refractive index.

9. The waveguide combiner of claim 8, wherein each of the first plurality of grating structures of the first grating is binary such that each of the first plurality of grating structures has sidewalls that are substantially perpendicular to the surface of the substrate.

10. The waveguide combiner of claim 9, wherein each of the second plurality of grating structures of the second grating are angled along an angled grating axis that is at an angle to a major axis of the substrate.

11. The waveguide combiner of claim 8, wherein materials of the first layer, the second layer, and the third layer of the first plurality of grating structures are the same as materials of the first layer, the second layer, and the third layer of the second plurality of grating structures.

12. The waveguide combiner of claim 8, wherein materials of the first layer, the second layer, and the third layer of the first plurality of grating structures are different from materials of the first layer, second layer, and third layer of the second plurality of grating structures.

13. The waveguide combiner of claim 8, wherein the first layer of the second plurality of grating structures extends along a major axis of the substrate within the second grating and covers the surface of the substrate such that the surface is not exposed in the second grating.
14. A waveguide combiner, comprising:
a substrate having a substrate refractive index;
a first layer of material disposed over the substrate, the first layer having a first refractive index; and
a grating comprising a plurality of grating structures, wherein each grating structure of the plurality of grating structures includes a multi-material layer stack comprising:
a second layer disposed on the first layer, the second layer having a second refractive index less than the first refractive index; and
a third layer disposed on the second layer, the third layer having a third refractive index less than the second refractive index.
15. The waveguide combiner of claim 14, wherein the second layer includes a residual portion between each grating structure of the plurality of grating structures.
16. The waveguide combiner of claim 14, further comprises a fourth layer disposed on the third layer, the fourth layer having a fourth refractive index less than the third refractive index.
17. The waveguide combiner of claim 14, wherein a difference between the first refractive index and the second refractive index is about 0.05 to about 0.2.
18. The waveguide combiner of claim 14, wherein a difference between the second refractive index and the third refractive index is between about 0.05 to about 0.2.
19. The waveguide combiner of claim 16, wherein a difference between the third refractive index and the fourth refractive index is about 0.05 to about 0.2.
20. A waveguide combiner, comprising:

a substrate having a substrate refractive index;
an input coupling grating; and
an output coupling grating, wherein each of the input coupling grating and the output coupling grating comprises a plurality of structures, and each grating structure of the plurality of structures includes a multi-material layer stack comprising:
a first layer of the multi-material layer stack disposed over a surface of the substrate, the first layer has a first refractive index;
a second layer disposed on the first layer, the second layer having a second refractive index less than the first refractive index; and
a third layer disposed on the second layer, the third layer having a third refractive index less than the second refractive index.