

WAVEGUIDE DESIGNS WITH LOW EYE-GLOW AND HIGH EFFICIENCY**BACKGROUND****Field**

[0001] Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to waveguide combiners with gratings that reduce eye-glow and increase efficiency.

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 (AR), 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 to 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. As an emerging technology, there are many challenges and design constraints with augmented reality.

[0004] One such challenge includes eye-glow generated by the AR device. Eye-glow generally refers to light that is visible on the world side of the AR device. Eye-glow results in distracting light projected on the world side from a waveguide of the augmented reality device. Accordingly, what is needed in the art are waveguides which reduce the amount of eye-glow projected on the world side of the augmented reality device.

SUMMARY

[0005] In an embodiment, a waveguide is provided. The waveguide includes a waveguide substrate and an incoupler grating disposed over the waveguide substrate. The incoupler grating comprises a plurality of blazed structures for incoupling light into the waveguide, and a metal coating is disposed over the plurality of blazed structures. The waveguide also includes an outcoupler grating disposed over the waveguide substrate. The outcoupler grating comprises a plurality of slant structures operable to out-couple light from the waveguide. Each of the plurality of slant structures comprises slant surfaces angled at a slant angle relative to a surface normal to the waveguide substrate in which the slant angle is greater than about 40 degrees.

[0006] In another embodiment, a waveguide is provided. The waveguide includes a waveguide substrate, and an incoupler grating disposed over a first surface of the waveguide substrate. The incoupler grating comprises a plurality of slant structures for incoupling light into the waveguide. The waveguide also includes an outcoupler grating disposed over a second surface of the waveguide substrate opposite the incoupler grating. The outcoupler grating comprising a second plurality of slant structures operable to out-couple light from the waveguide. Each of the second plurality of slant structures comprises slant surfaces angled at a slant angle relative to a surface normal to the waveguide substrate in which the slant angle is greater than about 40 degrees. A gap fill material is disposed between each of the second plurality of slant structures.

[0007] In a further embodiment, a waveguide is provided. The waveguide includes a waveguide substrate and an incoupler grating disposed over the waveguide substrate. The incoupler grating comprises a plurality of slant structures for incoupling light into the waveguide. The waveguide also includes an intermediate grating disposed over the waveguide substrate adjacent to the incoupler grating, and an outcoupler grating disposed over the waveguide substrate. The intermediate grating comprises a plurality of binary structures having sidewalls normal to the waveguide substrate, and the outcoupler grating

comprises a plurality of blazed structures operable to out-couple light from the waveguide. An encapsulation coating is disposed over a top surface of the plurality of blazed structures of the outcoupler grating.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] 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, may admit to other equally effective embodiments.

[0009] Figure 1 is a perspective, frontal view of a waveguide, according to certain embodiments.

[0010] Figures 2A and 2B are schematic, cross-sectional views of a waveguide, according to certain embodiments.

[0011] Figure 2C is a schematic, cross-sectional view of a blazed device structure, according to certain embodiments.

[0012] Figure 2D is a schematic, cross-sectional view of a waveguide, according to certain embodiments.

[0013] Figures 3A-3C are schematic, cross-sectional views of a waveguide, according to certain embodiments.

[0014] Figures 4A-4C are schematic, cross-sectional views of a portion of a waveguide, according to certain embodiments.

[0015] Figure 5 is a schematic, cross-sectional view of a portion of a waveguide, according to certain embodiments.

[0016] Figure 6 is a schematic, cross-sectional view of a portion of a waveguide, according to certain embodiments.

[0017] Figure 7 is a schematic, cross-sectional view of a portion of a waveguide, according to certain embodiments.

[0018] Figures 8A and 8B are schematic, cross-sectional views of a portion of a waveguide, according to certain embodiments.

[0019] Figures 9A and 9B are schematic, cross-sectional views of a portion of a waveguide, according to certain embodiments.

[0020] 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

[0021] The embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to waveguide combiners, such as augmented reality waveguide combiners with gratings to reduce eye-glow. Certain details are set forth in the following description and figures to provide a thorough understanding of various embodiments of the disclosure. Other details describing well-known structures and systems often associated with waveguide displays and gratings are not set forth in the following disclosure to avoid unnecessarily obscuring the description of the various embodiments.

[0022] Many of the details, dimensions, angles and other features shown in the Figures are merely illustrative of particular embodiments. Accordingly, other embodiments can have other details, components, dimensions, angles and features without departing from the spirit or scope of the present disclosure. In addition, further embodiments of the disclosure can be practiced without several of the details described below.

[0023] Augmented reality devices include a user field of view (FOV). The user FOV is a point at which a user perceives the virtual images of an

augmented reality display. The user FOV is determined by the angle of light reflected to the user's eye from the outcoupler grating of a waveguide. The light projects content (e.g., an image or text) toward the user. Light outcoupled from the waveguide may also be diffracted toward the world. The light exits the waveguide through the world side of the waveguide at the same angle it is projected into the waveguide by the incoupler grating. The light diffracted away from the user or exiting the waveguide through the world-side of the AR device is commonly referred to as "eye-glow," since the diffracted light is visible to the outside world by observers near the user. For near-eye display waveguides, high levels of eye-glow are undesirable, since the eye-glow can reduce visibility to the user's eyes, is distracting to others, and is typically a sign of low waveguide efficiency. Eye glow leads to low efficiency as the light leakage decrease the light out-coupled to the eyes of the user. Reducing eye glow will therefore correspondingly increase the efficiency of the waveguide. As described herein, light outcouples from the waveguide at the same angle the light is incoupled into the waveguide. Configuring the outcoupler of the waveguide to include gratings that are tuned to reflect light at the corresponding incoupling angles of light toward the user can reduce the amount of light that exits the waveguide on the world-side of the waveguide. As such, in some embodiments of the present disclosure, which can be combined with other embodiments, waveguide architectures configured to outcouple more light towards the user are provided to reduce eye-glow or the unwanted diffraction of light projecting from the world-side of the waveguide.

[0024] In evaluating eye-glow, a ratio between the efficiencies of light diffracted toward the user and light diffracted toward the world is considered based on the following equation:

$$\frac{\text{Efficiency (User side)}}{\text{Efficiency (World side)}} = \text{User/World Ratio}$$

$$\frac{1}{\text{User/World Ratio}} = \text{Eye-glow}$$

By increasing the efficiency of light diffracted towards the user and decreasing the efficiency of light diffracted toward the world, the User/World Ratio increases. As eye-glow is the inverse of the User/World Ratio, increasing User/World Ratio translates to a decrease in eye-glow. Accordingly, and as described above, a reduction in eye-glow by a waveguide may therefore also indicate a corresponding increased waveguide efficiency due to the reduction in leakage or out-coupling of eye-glow light to the world-side of the waveguide.

[0025] In certain embodiments, a waveguide having slant structures used as gratings for an outcoupler grating is provided. Without being bound by theory, it is believed that use of slant structures in the gratings of the outcoupler grating of the waveguide can allow for tuning and control of the portion and intensity of light being diffracted from the waveguide by the outcoupler grating toward the user and away from the user (i.e., toward the world) in order to control and minimize eye-glow. Specifically, the slant angle of the slant structures and tuned dimensions, such as grating height, residual layer height, grating top width, and grating bottom width, can be modified in any suitable manner to increase the portion of light diffracted towards the user and decrease the portion of light diffracted towards the world. For example, it was observed that, as compared to outcoupler grating formed using binary structures in which the User/World Ratio is between about 1.5:1 and about 2:1, slant structures can provide for a User/World Ratio between about 40:1 and about 60:1, depending on various other tuned dimensions of the grating. For example, in other embodiments, the waveguide including the structures of the outcoupler grating can further be modified to include blazed structures, slant structures having different shapes, one or more encapsulation coatings, one or more underlayers, and/or one or more grating materials to control and improve the corresponding efficiency of the waveguide to in turn minimize eye-glow.

[0026] Figure 1 is a perspective, frontal view of a waveguide 100. It is to be understood that the waveguide 100 described herein is an exemplary optical device. In some embodiments, which can be combined with other embodiments described herein, the waveguide 100 is a waveguide combiner,

such as an augmented reality waveguide combiner. The waveguide 100 may be a waveguide utilized in a near-eye display system. In another embodiment, which can be combined with other embodiments described herein, the waveguide 100 is a flat optical device, such as a metasurface.

[0027] The waveguide 100 includes a plurality of structures 102. The structures 102 may be disposed over, under, or on a top surface 101A of a substrate 101, or disposed in the substrate 101. In another embodiment, the structures 102 may be formed over, under, on, or in a grating material layer (not shown) disposed over the substrate 101. The structures 102 may include nanostructures having sub-micron dimensions, e.g., nano-sized dimensions. In some embodiments, which can be combined with other embodiments described herein, regions of the structures 102 correspond to one or more gratings 104. In some embodiments, which can be combined with other embodiments described herein, the waveguide 100 includes at least an incoupler grating 104A (e.g., an input-coupling grating) and an outcoupler grating 104C (e.g., an outcoupler grating). In some embodiments, which can be combined with other embodiments described herein, the waveguide 100 further includes an intermediate grating 104B (e.g., a pupil expander grating).

[0028] The structures/gratings of the incoupler grating of the waveguide 100 receives incident beams of light (a virtual image) having an intensity from a microdisplay. The incoupler grating splits the incident beams into a plurality of modes, each beam having a mode. Zero-order mode (T_0) beams are refracted back or lost in the waveguide 100, positive first-order mode (T_1) beams are coupled through the waveguide 100 to the intermediate gratings, and negative first-order mode (T_{-1}) beams propagate in the waveguide 100 in a direction opposite to the T_1 beams. Ideally, the incident beams are split into T_1 beams that have all of the intensity of the incident beams in order to direct the virtual image to the intermediate region. The T_1 beams coupled to the intermediate region are then split into T_0 beams refracted back or lost in the waveguide 100, T_1 beams that undergo TIR until the T_1 beams contact another grating of the

intermediate grating 104B, and T_{-1} beams that are coupled through the waveguide 100 to the outcoupler grating.

[0029] The T_{-1} beams coupled through the waveguide 100 to the outcoupler grating undergo TIR in the waveguide 100 until the T_{-1} beams contact the outcoupler grating 104C where the T_{-1} beams are split into T_0 beams refracted back or lost in the waveguide 100, T_1 beams that undergo TIR until the T_1 beams contact another grating of the outcoupler grating 104C, and T_{-1} beams coupled out of the waveguide 100. The T_1 beams that undergo TIR in the outcoupler grating continue to propagate until either the intensity of the T_{-1} beams coupled through the waveguide 100 to the outcoupler grating is depleted, or the remaining T_1 beams propagating through the outcoupler grating have reached the end of the outcoupler grating. The outcoupler grating 104C corresponding to the outcoupler grating of the waveguide 100 may be tuned to control the T_{-1} beams coupled through the waveguide 100 to the outcoupler grating in order to control the intensity of the T_{-1} beams coupled out of the waveguide 100. In some embodiments, the outcoupler grating 104C may be formed with slant grating structures to tune and control each of the portion or intensities of light being diffracted from the outcoupler grating toward the user and away from the user (i.e., toward the world). In such embodiments, one approach to control the T_{-1} beams passed through the waveguide 100 to the outcoupler grating is to optimize a slant angle of the slant structures for the outcoupler grating 104C to modulate the field of view and increase the viewing angle. Moreover, modulating the slant angle and/or other dimensions of the slant structures can provide for modulating a ratio between the portion of light diffracted towards the user and light diffracted towards the world.

[0030] Figures 2A and 2B are schematic, cross-sectional views of a waveguide 100, according to certain embodiments. As shown in Figure 2A, the waveguide 100 includes a substrate 101, a grating material layer 202 disposed over a top surface 101A of the substrate 101, and an anti-reflective (AR) coating 203 disposed on a bottom surface 101B of the substrate 101 opposite the top surface 101A. In certain embodiments, the waveguide 100 also includes a

plurality of blazed structures 204 corresponding to the incoupler grating 104A of the waveguide 100 i.e., an input-coupling grating of the waveguide 100, a plurality of binary structures 206 corresponding to the intermediate grating 104B of the waveguide 100 i.e., a pupil expansion grating of the waveguide 100, and a plurality of slant structures 208 corresponding to the outcoupler grating 104C i.e., an outcoupler grating of the waveguide 100.

[0031] In certain embodiments, the blazed structures 204 of the incoupler grating 104A may be disposed in (as shown in Figure 2A) or on (as shown in Figure 2B) the grating material layer 202. In an embodiment, the waveguide 100 may be an augmented reality waveguide combiner for use in a near-eye display system. The plurality of blazed structures 204 (as described below in reference to Figure 2D) can therefore modulate light projected towards the waveguide 100 and incouple the light into the waveguide 100.

[0032] Figure 2C illustrates a schematic, cross-sectional view of a blazed structure 204 according to one or more embodiments of the present disclosure. Referring to FIG. 2C, the blazed structure 204 includes a first blazed surface 205, a second blazed surface 207 opposite the first blazed surface 205, a top surface 209, a bottom surface 211 opposite the top surface 209, a grating depth "h," a top width " T_w ," a bottom width " B_w ," and a linewidth "d." The grating depth "h" can be from about 10 nanometers to about 500 nanometers; for example, from about 50 nanometers to about 80 nanometers; or from about 20 nanometers to about 40 nanometers. The first blazed surface 205 forms a blaze angle "A." The blaze angle "A" can be from about 50 degrees to about 80 degrees relative to a plane 213 normal to the substrate 101, for example, from about 60 degrees to about 70 degrees from the plane 213. The second blazed surface 207 forms a blaze angle "B." The blaze angle "B" can be from about 0 degrees to about 40 degrees from the plane 213, for example, from about 10 degrees to about 30 degrees from the plane 213. A top duty cycle is defined as (Top width T_w / grating period). The top duty cycle can be from about 0% to about 40%, for example, from about 10% to about 20%. A bottom duty cycle is defined as (Bottom width B_w / grating period). The bottom duty cycle

can be from about 55% to about 100%, for example, from about 60% to about 80%.

[0033] In some embodiments, which can be combined with other embodiments described herein, the blaze angles “A” and/or “B” of two or more blazed structures 106 are different. In another embodiment, which can be combined with other embodiments described herein, the blaze angles “A” and/or “B” of two or more blazed structures 106 are the same. In some embodiments, which can be combined with other embodiments described herein, the depth *h* of two or more blazed structures 204 are different. In another embodiment, which can be combined with other embodiments described herein, the depth *h* of two or more blazed structures 204 are the same.

[0034] In an embodiment, the incoupler grating 104A may also include a metal coating 210 disposed over the plurality of blazed structures 204 to improve the incoupling efficiency of the incoupler grating 104A. In some embodiments, which can be combined with other embodiments described herein, the metal coating 210 comprises, consists of, or consists essentially of one or more metals. The metal coating 210 may include, but is not limited to transparent conducting materials (e.g., indium-tin-oxide (ITO), fluorine doped tin oxide (FTO), or doped zinc oxide), silver, aluminum, gold, or a combination thereof. In an embodiment, the metal coating 210 is aluminum. The metal coating 210 can be of any suitable shape. In some embodiments, which can be combined with other embodiments, the metal coating 210 forms a conformal coating over (as shown in Figure 2A) or on (as shown in Figure 2B) the blazed structures 204. In other embodiments, which can be combined with other embodiments, the metal coating 210 forms a blanket coating or overfills the patterns defined by the blazed structures 204. In some embodiments, which can be combined with other embodiments described herein, the metal coating 120 has a thickness from about 10 nanometers to about 100 nanometers; for example, from about 50 nanometers to about 80 nanometers; or from about 20 nanometers to about 40 nanometers.

[0035] The plurality of binary structures 206 of the intermediate grating 104B may be formed in (as shown in Figure 2A) the grating material layer 202. Each of the plurality of binary structures 206 are separated by a gap (e.g., trench). The binary structures 206 each include a pair of sidewalls that are substantially parallel with one another and are each substantially perpendicular with a bottom surface of the gap between each of the plurality of binary structures 206. In some embodiments, which can be combined with other embodiments described herein, the depths of two or more binary structures 206 are different. In another embodiment, which can be combined with other embodiments described herein, the depth of two or more binary structures 206 is the same.

[0036] The plurality of slant structures 208 of the outcoupler grating 104C may also be formed in (as shown in Figure 2A) the grating material layer 202. The slant structures 208 include structures that are angled such that each of the sidewalls of the structure 208 form a non-perpendicular angle with a corresponding bottom surface of a gap between each of the slant structures 208. Each of the plurality of slant structures 208 includes a height h and a lateral distance d . The height h of the structures 208 is defined as the distance from a top surface 214A of the underlayer 214 to a top surface 208A of the structures 208. A gap g is the distance between adjacent slant structures 208 of the outcoupler grating 104C. In some embodiments, the gap g between each of the adjacent slant structures 208 of the plurality of slant structures 208 is substantially the same. In another embodiment, the gap g of at least one set of structures 208 is different from the gap g of additional sets of adjacent slant structures 208 of the plurality of slant structures 208. In some embodiments, each of the plurality of slant structures 208 of the outcoupler grating 104C may have the same slant angle θ' relative to a plane 408 normal to the substrate 101 or the underlayer 214 (if present). In some embodiments, some of the structures 208 are formed with a different slant angle θ' relative to the surface 208 than other slant structures 208 of the plurality of slant structures 208. In some embodiments, the material of the grating material layer 202 for forming the plurality of slant structures may be selected based on the desired depth and slant angle of the structures 208. In some embodiments, the structures 208 may

have a slant angle θ' greater than about 40 degrees relative to the plane 408, for example, the slant angle θ' may be about 45 degrees, 50 degrees, or 55 degrees.

[0037] In embodiments of the waveguide 100 in which the structures of the incoupler grating 104A, intermediate grating 104B, and outcoupler grating 104C are all formed in the grating material layer 202, as shown in Figure 2A, only a single grating material layer 202 is deposited over the substrate 101 for the waveguide 100, and a top surface of each of the structures 204, 206, 208 is substantially co-planar with a top surface 202A of the grating material layer 202.

[0038] Any suitable method for deposition of the grating material layer 202 can be used. Examples of suitable thin film deposition methods include a physical vapor deposition (PVD) process (e.g., ion beam sputtering, magnetron sputtering, e-beam evaporation), a chemical vapor deposition (CVD) process, a plasma enhanced chemical vapor deposition (PECVD) process, an atomic layer deposition (ALD) process, an inkjet printing process, or a three-dimensional (3D) printing process.

[0039] In an embodiment, which can be combined with other embodiments described herein, the structures 204, 206, 208 may be formed by performing one or more of an etch process in the grating material layer 202. For example, the etch process for forming the blazed structures 204 and the binary structures 206 may include, without limitation, at least one of ion beam etching (IBE), e-beam etching, or reactive ion etching (RIE). The etch process for forming the slant structures 208 of the outcoupler grating 104C may be formed by performing an angled etch process in the grating material layer 202.

[0040] In another embodiment, the blazed structures 204 may be formed by performing an imprint process. For example, as shown in Figure 2B, the blazed structures 204 may be formed by locally depositing an imprintable material over the top surface 202A of a portion of the grating material layer 202 and imprinting the imprintable material to form the blazed structures 204. In certain embodiments, the nanoimprint resist may include at least one of spin on glass

(SOG), flowable SOG, organic, inorganic, and hybrid (organic and inorganic) nanoimprintable materials that may contain at least one of silicon oxycarbide (SiOC), titanium dioxide (TiO₂), silicon dioxide (SiO₂), vanadium (IV) oxide (VO_x), aluminum oxide (Al₂O₃), indium tin oxide (ITO), zinc oxide (ZnO), tantalum pentoxide (Ta₂O₅), silicon nitride (Si₃N₄), titanium nitride (TiN), and zirconium dioxide (ZrO₂) containing materials.

[0041] In another embodiment, the waveguide 100 also includes a gapfill material 212 disposed between each of the slant structures 208 of the outcoupler grating 104C. The gapfill material 212 may likewise be used to improve the output-coupling efficiency of the outcoupler grating 104C and made of a material with a refractive index substantially matched to or greater than the refractive index of the material of the slant structures 208 (i.e., the grating material layer 202).

[0042] In certain embodiments, the gapfill material 212 may include at least one of SOG, flowable SOG, organic nano imprintable, inorganic nano imprintable, and hybrid (organic and inorganic) nano imprintable materials, such as at least one of SiOC, TiO₂, SiO₂, VO_x, Al₂O₃, ITO, ZnO, Ta₂O₅, Si₃N₄, TiN, and ZrO₂ containing materials. In certain embodiments, the gapfill material 212 may be deposited between each of the slant structures 208 using a liquid material pour casting process, a spin-on coating process, a liquid spray coating process, a dry powder coating process, a screen printing process, a doctor blading process, a PVD process, a CVD process, a FCVD process, or an ALD process.

[0043] The substrate 101 can be any substrate used in the art, and can be either opaque or transparent to a chosen wavelength of light, depending on the use of the substrate 101 as a substrate for a waveguide. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, polymers, or combinations thereof. In some embodiments, the substrate 101 includes, but is not limited to, a silicon-containing material, a silicon and oxygen containing compound, a germanium-containing material, a indium and

phosphide containing compound, a gallium and arsenic containing compound, a gallium and nitrogen containing compound, a carbon-containing material, a silicon and carbon containing compound, a silicon, carbon, and oxygen containing compound, a silicon and nitrogen containing compound, a silicon, oxygen, and nitrogen containing compound, a niobium and oxygen containing compound, and lithium, niobium, and oxygen containing compound, an aluminum and oxygen containing compound, a indium, tin, and oxygen containing compound, a titanium and oxygen containing compound, a lanthanum and oxygen containing compound, a gadolinium and oxygen containing compound, a zinc and oxygen containing compound, a yttrium and oxygen containing compound, a tungsten and oxygen containing compound, a potassium, and oxygen containing compound, a phosphorous and oxygen containing compound, a barium and oxygen containing compound, a sodium and oxygen containing compound, or combinations thereof. In other embodiments, which can be combined with other embodiments described herein, the substrate 101 includes an oxide including one or more of gadolinium, silicon, sodium, barium, potassium, tungsten, phosphorus, zinc, calcium, titanium, tantalum, niobium, lanthanum, zirconium, lithium, or yttrium containing-materials. Example materials of the substrate 101 include silicon (Si), silicon monoxide (SiO), silicon dioxide (SiO₂), silicon carbide (SiC), fused silica, diamond, quartz germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), sapphire, sapphire (Al₂O₃), lithium niobate (LiNbO₃), indium tin oxide (ITO), lanthanum oxide (La₂O₃), gadolinium oxide (Gd₂O₃), zinc oxide (ZnO), yttrium oxide (Y₂O₃), tungsten oxide (WO₃), titanium oxide (TiO₂), zirconium oxide (ZrO₃), sodium oxide (Na₂O), niobium oxide (Nb₂O₅), barium oxide (BaO), potassium oxide (K₂O), phosphorus pentoxide (P₂O₅), calcium oxide (CaO), or combinations thereof.

[0044] In such an embodiment, the grating material layer 202 and the substrate 101 include a different material. The grating material layer 202 may include, but is not limited to, one or more oxides, carbides, or nitrides of silicon, aluminum, zirconium, tin, tantalum, zirconium, barium, titanium, hafnium,

lithium, lanthanum, cadmium, niobium, or combinations thereof. Example materials of the grating material layer 202 include silicon carbide, silicon oxycarbide, titanium oxide, titanium dioxide, silicon oxide, silicon dioxide, vanadium oxide, aluminum oxide, aluminum-doped zinc oxide, indium tin oxide, tin oxide, zinc oxide, tantalum oxide, tantalum pentoxide, silicon nitride, titanium nitride, zirconium oxide, zirconium dioxide, niobium oxide, cadmium stannate, silicon oxynitride, barium titanate, diamond like carbon, hafnium oxide, lithium niobate, silicon carbon-nitride, silver, cadmium selenide, mercury telluride, zinc selenide, silver-indium-gallium-sulfur, silver-indium-sulfur, indium phosphide, gallium phosphide, lead sulfide, lead selenide, zinc sulfide, molybdenum sulfide, tungsten sulfide, or combinations thereof. In some embodiments, which can be combined with other embodiments described herein, the material of the grating material layer 202 may have a refractive index between about 1.5 and about 2.65, such as between about 2.0 and 2.6. In other embodiments, which can be combined with other embodiments described herein, the material of the grating material layer 202 may have a refractive index of about 2.1, about 2.3, or about 2.5.

[0045] Figure 2C shows another embodiment of the waveguide 100. As shown in Figure 2C, the incoupler grating 104A, intermediate grating 104B, and outcoupler grating 104C may each be formed from a grating material layer 202 separately and locally disposed over a portion of the substrate 101. In an embodiment, the grating material layers 202 for forming each of the blazed structures 204, binary structures 206, and slant structures 208 may be deposited to a different thickness to provide for varying the size and tuned dimensions (e.g., height) of the structures 204, 206, 208 subsequently formed therein. Accordingly, in contrast to the top surface of the structures 204, 206, 208 in waveguide 100 being co-planar with the top surface 202A of the grating material layer 202, a top surface of each of the structures 204, 206, 208 in waveguide 220 may be varied, as shown in Figure 2C.

[0046] In another embodiment, instead of etching a locally deposited grating material layer 202 to form the blazed structures 204, the blazed structures 204

of waveguide 220 may be formed by imprinting a locally deposited imprintable material as discussed above for waveguide 100. Similar to waveguide 100, waveguide 220 may also include the metal coating 210 disposed on the blazed structures 204 in the incoupler grating 104A as well as the gapfill material 212 disposed between each of the slant structures 208 in the outcoupler grating 104C, as shown in Figure 2C.

[0047] In an embodiment, which may be combined with other embodiments herein, the waveguide 220 may also include an underlayer 214 disposed between the structures 204, 206, 208 and the substrate 101, as shown in Figure 2C. The underlayer 214 may be of a material with a different refraction index from the grating material layer 202 utilized for forming the structures 204, 206, 208. Similar to waveguide 100 discussed above, the blazed structures 204 may be formed by an imprint or etch process, the binary structures 206 may be formed by an etch process, and the slant structures 208 may be formed by an angled etch process.

[0048] Figures 3A-3C are cross-sectional views of the waveguide 100, according to certain embodiments. In an embodiment, the incoupler grating 104A of the waveguide 100 may alternatively be formed with slant structures 304. The waveguide 100 may also include binary structures 206 corresponding to the intermediate grating 104B of the waveguide 100 i.e., a pupil expansion region of the waveguide 100, and slant structures 208 corresponding to the outcoupler grating 104C i.e., an outcoupler grating of the waveguide 100. The slant structures 304, binary structures 206, and slant structures 208 may be disposed on the underlayer 214 (as shown in Figure 3A) or in the grating material layer 202 (as shown in Figure 3B). In an embodiment, the slant structures 304 may be formed in a similar manner as the slant structures 208 discussed above. For example, the slant structures 304 may be formed using an angled etch process. In an embodiment, the slant structures 304 may have a slant angle θ' that is between about 10 degrees and about 60 degrees. In an embodiment, the slant structures 304 may also include a gapfill material (not shown) disposed between each of the slant structures 304.

[0049] The slant structures 304, binary structures 206, and slant structures 208 formed on the underlayer 214 may be formed with varying heights, as shown in Figure 3A. As with the waveguide 100 discussed above in Figure 2C, each of the slant structures 304, binary structures 206, and slant structures 208 may be formed from a grating material layer 202 separately and locally disposed over a portion of the substrate 101 or the underlayer 214 (if present).

[0050] In another embodiment, the slant structures 304 of the incoupler grating 104A may be formed on the bottom surface 101B of the substrate 101 opposite from the intermediate and outcoupler gratings 104B, 104C on the top surface 101A of the substrate 101. As shown in Figure 3C, the slant structures 304 of the incoupler grating 104A may be formed from a grating material layer 202 locally deposited on a portion of the bottom surface 101B of the substrate 101 adjacent to the AR coating 203.

[0051] Figures 4A-4C are cross-sectional views of an outcoupler grating of the waveguide 100, according to certain embodiments. In an embodiment, the outcoupler grating 104C for the outcoupler grating of the waveguide 100 includes the plurality of the slant structures 208 formed over the underlayer 214. In certain embodiments, the waveguide 100 also includes a second underlayer 404 disposed between the plurality of slant structures 208 and the substrate 101. As shown in Figure 4B, the waveguide 100 may include the second underlayer 404 further formed between the underlayer 214 and the substrate 101. Use of more than one underlayer provides for additional flexibility to tune the efficiency of the waveguide 100. In an embodiment, a refractive index of the second underlayer 404 may be different from a refractive index of the underlayer 214 and/or a refractive index of the material of the slant structures 208. In an embodiment, the underlayer 214 is made of a material having a refractive index of about 2.2 and the second underlayer 404 is made of a material having a refractive index of about 2.5.

[0052] As shown in Figure 4C, the waveguide 100 may also include a second anti-reflective (AR) coating 406 disposed on a second surface 203B of the AR coating 203 opposite the substrate 101. In an embodiment, a refractive

index of the second AR coating 406 is between about 1.4 and about 2.0. In an embodiment, the refractive index of the second AR coating 406 is different from the refractive index of the AR coating 203 and/or the substrate 101.

[0053] In certain embodiments, the waveguide 100 includes an encapsulation coating 402 disposed over the plurality of slant structures 208 of the outcoupler grating 104C. The encapsulation coating 402 includes a planar surface formed over the structures 208 of the outcoupler grating 104C using a flat coating process, such as a FCVD, a PVD, or a spin-on coating process. In an embodiment, the encapsulation coating 402 may include materials having a refractive index lower or different than that of the grating material of the slant structures 208 i.e., the grating material layer 202. In some embodiments, the refractive index of the encapsulation coating 402 is between about 1.0 and about 1.7, such as between about 1.2 and about 1.5. In some embodiments, the encapsulation coating 402 has an absorption coefficient less than about 0.001. The encapsulation coating 402 may be formed of any suitable transparent materials, including but not limited to silica-containing materials and non-silica-containing materials, such as polymer-containing materials, for example, fluoropolymer materials. In some embodiments, the encapsulation coating 402 is formed of silicon dioxide (SiO₂) or a low-k dielectric films such as carbon- and nitride-doped silicon oxide (SiCON) or silicon carbon nitride (SiCN). In some embodiments, the encapsulation coating 402 includes fluorine-containing materials, such as aluminum fluoride (AlF₃) and magnesium fluoride (MgF₂). In other embodiments, the encapsulation coating 402 and the substrate 101 or the grating material layer 202 are formed of substantially the same materials.

[0054] Figures 5 and 6 are cross-sectional views of an outcoupler grating of the waveguide 100, according to certain embodiments. In an embodiment, the outcoupler grating 104C of the waveguide 100 may include a plurality of slant structures 508 formed with a tilted bottom surface 502 extending from a trailing sidewall 506 towards a leading sidewall 504 of an adjacent structure 508. For example, as shown in Figure 5, the bottom surface 502 of a gap (e.g., trench)

between each of the slant structures 508 may be angled away from the top surface 214A of the underlayer 214 so as to form an inclined surface towards the leading sidewall 504 of adjacent structure 508.

[0055] In another embodiment, as shown in Figure 6, the outcoupler grating 104C of the waveguide 100 may be formed to include a plurality of blazed structures 608. The plurality of blazed structures 608 may be similar to the blazed structures 204 discussed above. The blazed structures 608 may be formed in the grating material layer 202 disposed over the substrate 101. The blazed structures 608 may be formed from a locally deposited grating material layer 202 disposed on the substrate 101 or one or more underlayers (i.e. the underlayer 214 and second underlayer 404). The blazed structures 608 may be formed using an etch process or an imprint lithography process. The outcoupler grating 104C formed according to the embodiments shown in Figures 5 and 6 may also include the encapsulation coating 402 disposed over the blazed structures 608.

[0056] Figure 7 is a cross-sectional view of an outcoupler grating of the waveguide 100, according to certain embodiments. In an embodiment, the waveguide 100 includes a plurality of slant structures 704. The slant structures 704 may be formed from a first grating material 706 and a second grating material 708 different from the first grating material 706. The first grating material 706 and the second grating material 708 may be any of the materials described above with respect to the grating material layer 202. The slant structures 704 may be formed by depositing the second grating material 708 over the top surface 101A of the substrate 101 (or one or more underlayers, if present), depositing the first grating material 706 over the second grating material 708, and etching the first grating material 706 and second grating material 708 to form the plurality of slant structures 704. The first grating material 706 may have a refractive index substantially matched to or greater than the refractive index of the second grating material 708.

[0057] In an embodiment, the plurality of slant structures 704 may also include a gapfill material (not shown) similar to the gapfill material 212

discussed above disposed between each of the plurality of slant structures 704. The waveguide 100 may also include an encapsulation coating 702 formed over the plurality of slant structures 704. The encapsulation coating 702 may be formed as a conformal coating disposed over the slant structures 704 of the outcoupler grating 104C. Examples of suitable thin film deposition methods for forming the encapsulation coating 702 as a conformal coating include physical vapor deposition (PVD) (e.g., ion beam sputtering, magnetron sputtering, e-beam evaporation), chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), atomic layer deposition (ALD), and inkjet printing.

[0058] Figures 8A and 8B are cross-sectional views of an outcoupler grating of the waveguide 100, according to certain embodiments. In an embodiment, the outcoupler grating 104C may include the plurality of slant structures 208 described above and an encapsulation coating comprising more than one material disposed thereover. For example, the outcoupler grating 104C may include the encapsulation coating 402 discussed above and a second coating 802 disposed over the structures 208 of the outcoupler grating 104C. In certain embodiments, a portion of the plurality of slant structures 208 may be in contact with each of the encapsulation coating 402 and the second coating 802, as shown in Figure 8A. In other embodiments, the plurality of slant structures 208 may be completely encased by the encapsulation coating 402 with the second coating 802 subsequently disposed over a top surface 402A of the encapsulation coating 402, as shown in Figure 8B. In such an embodiment, the encapsulation coating 402 overfills the pattern defined by the plurality of slant structures 208 and forms a planarized surface over the structures 208.

[0059] Figures 9A and 9B are cross-sectional views of an outcoupler grating of the waveguide 100, according to certain embodiments. In an embodiment, the outcoupler grating 104C of the waveguide 100 may include the plurality of slant structures 208 discussed above. The slant structures 208 may be formed over an underlayer 902 having a non-planar profile disposed over the substrate 101. For example, as shown in Figure 9A, the underlayer 902 may be formed

with a linear tapered profile in which a thickness of the underlayer 902 increases from one portion of the underlayer 902 to another. The tapered profile of the underlayer 902 may be formed using an etch process, such as a selective area processing (SAP) etch to remove portions of the underlayer 902. The plurality of slant structures 208 may then be formed over the underlayer 902. In another embodiment, as shown in Figure 9B, the underlayer 904 may be formed with a profile of varying thicknesses over the substrate 101 having a plurality of peaks. The underlayer 904 may be formed using a gray tone lithography process. The plurality of slant structures 208 may then be formed over the underlayer 904.

[0060] In summation, the embodiments of the present disclosure described herein relate to waveguide combiners having different incoupler grating and outcoupler grating designs. The different designs provide the benefits of lower eye-glow and improved efficiency.

[0061] 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, comprising:
a waveguide substrate;
an incoupler grating disposed over the waveguide substrate, the incoupler grating comprising a plurality of blazed structures for incoupling light into the waveguide, and a metal coating disposed over the plurality of blazed structures; and
an outcoupler grating disposed over the waveguide substrate, the outcoupler grating comprising a plurality of slant structures operable to out-couple light from the waveguide, wherein each of the plurality of slant structures comprises slant surfaces angled at a slant angle relative to a surface normal to the waveguide substrate, and the slant angle is greater than about 40 degrees.
2. The waveguide of claim 1, further comprising a gap fill material disposed between each of the plurality of slant structures.
3. The waveguide of claim 1, further comprising an intermediate grating disposed over the waveguide substrate, the intermediate grating comprising a plurality of binary structures having sidewalls normal to the waveguide substrate.
4. The waveguide of claim 1, wherein the incoupler grating and the outcoupler grating are formed in a grating material layer disposed over the waveguide substrate, and a top surface of the plurality of blazed structures is substantially coplanar with a top surface of the plurality of slant structures.
5. The waveguide of claim 1, wherein the plurality of slant structures are formed in a grating material layer disposed over the waveguide substrate, and the plurality of blazed structures comprises an imprintable material disposed on the grating material layer.
6. The waveguide of claim 1, further comprising an anti-reflective coating disposed on a surface of the waveguide substrate opposite of the incoupler grating and the outcoupler grating.

7. The waveguide of claim 1, further comprising an underlayer disposed between the plurality of slant structures and the waveguide substrate, wherein the plurality of slant structures comprises a grating material having a refractive index different from a refractive index of the underlayer.

8. The waveguide of claim 1, further comprising an encapsulation coating disposed over a top surface of the plurality of slant structures, wherein the plurality of slant structures comprises a grating material having a refractive index different from a refractive index of the encapsulation coating.

9. The waveguide of claim 8, wherein the encapsulation coating comprises a conformal coating disposed over the plurality of slant structures of the outcoupler grating.

10. The waveguide of claim 1, wherein the plurality of slant structures comprises a first grating material disposed over a second grating material, and the first grating material is different from the second grating material.

11. A waveguide, comprising:

a waveguide substrate;

an incoupler grating disposed over a first surface of the waveguide substrate, the incoupler grating comprising a first plurality of slant structures for incoupling light into the waveguide;

an outcoupler grating disposed over a second surface of the waveguide substrate opposite the incoupler grating, the outcoupler grating comprising a second plurality of slant structures operable to out-couple light from the waveguide, wherein each of the second plurality of slant structures comprises slant surfaces angled at a slant angle relative to a surface normal to the waveguide substrate, and the slant angle is greater than about 40 degrees; and

a gap fill material disposed between each of the second plurality of slant structures.

12. The waveguide of claim 11, further comprising an intermediate grating disposed over the waveguide substrate, the intermediate grating comprising a plurality of binary structures having sidewalls normal to the waveguide substrate.

13. The waveguide of claim 11, further comprising an anti-reflective coating disposed over the first surface of the waveguide substrate adjacent the incoupler grating.

14. The waveguide of claim 11, further comprising an underlayer disposed between the second plurality of slant structures and the waveguide substrate, wherein the second plurality of slant structures comprises a grating material having a refractive index different from a refractive index of the underlayer.

15. The waveguide of claim 11, further comprising an encapsulation coating disposed over a top surface of the second plurality of slant structures, wherein the second plurality of slant structures comprises a grating material having a refractive index different from a refractive index of the encapsulation coating.

16. A waveguide, comprising:

a waveguide substrate;

an incoupler grating disposed over the waveguide substrate, the incoupler grating comprising a plurality of slant structures for incoupling light into the waveguide;

an intermediate grating disposed over the waveguide substrate adjacent to the incoupler grating, the intermediate grating comprising a plurality of binary structures having sidewalls normal to the waveguide substrate;

an outcoupler grating disposed over the waveguide substrate, the outcoupler grating comprising a plurality of blazed structures operable to out-couple light from the waveguide; and

an encapsulation coating disposed over a top surface of the plurality of blazed structures of the outcoupler grating.

17. The waveguide of claim 16, further comprising a gapfill material disposed between each of the plurality of slant structures of the incoupler grating.

18. The waveguide of claim 16, further comprising an underlayer disposed between the plurality of blazed structures and the waveguide substrate, wherein the plurality of blazed structures comprises a grating material having a refractive index different from a refractive index of the underlayer.

19. The waveguide of claim 16, further comprising an anti-reflective coating disposed on a surface of the waveguide substrate opposite of the incoupler grating and the outcoupler grating.

20. The waveguide of claim 16, further comprising a second encapsulation coating different from the encapsulation coating disposed over a top surface of the encapsulation coating.