SLAB WAVEGUIDE LAYER FOR ENHANCED NEAR-EYE-DISPLAY SURFACE RELIEF GRATING LIGHTGUIDE

BACKGROUND

Field

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

Description of the Related Art

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

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

[0004] One such challenge is displaying a virtual image overlaid on an ambient environment. Waveguide combiners are used to assist in overlaying images. Generated light is in-coupled into a waveguide combiner, propagated through the augmented waveguide combiner, out-coupled from the augmented waveguide combiner, and overlaid on the ambient environment. Light is coupled into and out of augmented waveguide combiners using surface relief gratings. Accordingly, what is needed in the art are waveguide combiners.

SUMMARY

[0005] In one embodiment, a waveguide is provided. The waveguide includes a waveguide substrate, having a substrate refractive index (RI) n_{sub}, a slab waveguide

layer disposed over the waveguide substrate, the slab waveguide layer having a slab RI n_{swg} and a slab depth d_{swg}, the slab depth d_{swg} from a lower surface to an upper surface of the slab waveguide layer, at least one grating defined by a plurality of grating structures, the grating structures are disposed in, on, or over the slab waveguide layer, and a superstrate between and over the grating structures, the superstrate having a superstrate RI $n_{superstrate}$ and an interface with the slab waveguide layer. The slab RI n_{swg} is greater than the substrate RI n_{sub} and the slab RI n_{swg} is greater than the superstrate RI $n_{superstrate}$.

[0006] In one embodiment, a waveguide is provided. The waveguide includes a waveguide substrate, having a substrate refractive index (RI) n_{sub}, a slab waveguide layer disposed over the waveguide substrate, the slab waveguide layer having a slab RI n_{swg} and a slab depth d_{swg}, the slab depth d_{swg} from a lower surface to an upper surface of the slab waveguide layer, at least one grating defined by a plurality of grating structures, the grating structures are disposed in, on, or over the slab waveguide layer, a superstrate between and over the grating structures, the superstrate having a superstrate RI $n_{superstrate}$ and an interface with the slab waveguide layer. The slab RI n_{swg} is greater than the substrate RI n_{sub} and the slab RI n_{swg} is greater than the superstrate RI $n_{superstrate}$, and the slab depth d_{swg} is 75 nm to 110 nm when the slab RI n_{swg} at 620 nm is 2.1, 55 nm to 100 nm when the slab RI n_{swg} at 620 nm is 2.2, 35 nm to 85 nm when the slab RI n_{swg} at 620 nm is 2.3, 30 nm to 70 nm when the slab RI n_{swg} at 620 nm is 2.4, 25 nm to 60 nm when the slab RI n_{swg} at 620 nm is 2.5, and 15 nm to 50 nm when the slab RI n_{swg} at 620 nm is 2.6.

[0007] In one embodiment, a waveguide is provided. The waveguide a waveguide substrate, having a substrate refractive index (RI) n_{sub}, a slab waveguide layer disposed over the waveguide substrate, the slab waveguide layer having a slab RI n_{swg} and a slab depth d_{swg}, a fold grating defined by grating structures disposed in the slab waveguide layer, the slab depth d_{swg} is from a lower surface to an upper surface of the slab waveguide layer between grating structures, and a superstrate between and over the grating structures, the superstrate having a superstrate RI $n_{superstrate}$ and an interface with the slab waveguide layer, wherein the slab RI n_{swg} is greater than the substrate RI n_{sub} and the slab RI n_{swg} is greater than the superstrate RI $n_{superstrate}$.

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, and may admit to other equally effective embodiments.

[0009] Figure 1A is a cross-sectional view of a waveguide according to embodiments.

[0010] Figure 1B is a k-space diagram of a waveguide according to embodiments.

[0011] Figure 2 is a cross-sectional view of a waveguide according to embodiments.

[0012] Figure 3 is graph of simulated diffraction efficiency of three waveguides.

[0013] Figures 4A-4C are cross-sectional views of a waveguide according to different configurations.

[0014] Figures 5A-5E are cross-sectional views of gratings according to embodiments.

[0015] 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

[0016] Embodiments of the present disclosure generally relate to augmented reality waveguide combiners.

[0017] Figure 1A is a cross-sectional view of a waveguide 100. The waveguide 100 includes a waveguide substrate 101. An in-coupler 102, a first grating (e.g., fold grating) 104, and a second (e.g., out-coupler) grating 106 are disposed over the

waveguide substrate 101. The in-coupler 102, the first grating 104, and the second grating 106 include grating structures 108. The grating structures 108 include a device material 103 disposed over the waveguide substrate 101.

[0018] Figure 1B is a k-space diagram of the waveguide 100. In operation, white light is incoupled by the in-coupler 102 and undergoes total-internal-reflection (TIR) through the waveguide 100 to the fold grating. A blue channel light (wavelengths of 380 nm to about 495 nm), a green channel light (wavelength of about 495 nm to about 590 nm), a red channel light (wavelength of about 590 nm to about 750 nm) propagate under total internal reflection (TIR) at different decay rates. Beams of the light channels (blue, green, and red channel light) undergo TIR in ther fold grating until the beams of the light channels are coupled to the out-coupler 106. The beams outcoupled by the out-coupler 106 out of the waveguide 100 results in field of view of a virtual image that are projected user's eye. The fields of view include a blue field of view (FOV), a green FOV, and a red FOV.

[0019] Due to dispersion of diffracted angles of propagation inside the waveguide 100, the density of interactions with the grating surfaces is lower for longer wavelengths (red channel light) than shorter wavelengths (blue channel light). The angular dispersion due to diffraction is shown by the diffraction equation:

$$\theta_o = \text{asin}\left(\frac{1}{n_o} sin(\theta_i) +/- \frac{m\lambda_0}{n_i \Lambda}\right)$$

where θ_o is the output diffracted angle, θ_i is the input angle, λ_0 is the free-space wavelength, Λ is the grating period, $n_o$is the output medium refractive index, n_i is the input medium refractive index, and m is the diffracted order (…,-2, -1, 0 ,+1, +2, …). As wavelength increases, the diffracted angle increases.

[0020] As shown in Figure 1B, at a first TIR state 107 and a second TIR state 109, the dispersion of propagation angles in TIR between the blue channel light, the green channel light, and the red channel light results in a blue FOV 111, a green FOV 113, and a red FOV 115 offset from each other. There is stronger out-coupling of the blue channel light in the corner of the display field-of-view nearest the projector 105, along with faster decay of blue light as the blue channel light propagates to out-coupler 106 furthest from the projector. The red channel light decays more slowly as the red light

propagates, and thus dominates the image in the portion of the field-of-view furthest from the projector 105. It is desired minimize the number of substrates required in the near-eye-display, however when multiple display channels (blue, green, red channels) are intended to propagate through a waveguide substrate 101 the diffraction efficiency of the multiple display channels need to be improved.

[0021] Figure 2 is a cross-sectional view of a waveguide 200. The waveguide of 200 of Figure 2 has a first configuration 401. The waveguide 200 includes a waveguide substrate 201. The waveguide substrate 201 has a substrate refractive index (RI) n_{sub}.

[0022] The waveguide 200 includes at least one grating defined by a plurality of grating structures 208. The waveguide 200 includes an in-coupler 202, a first grating (e.g., fold grating) 204, and a second grating (e.g., out-coupler) 206. The in-coupler 202, the first grating 204, and the second grating 206 include grating structures 208. A slab waveguide layer 210 is disposed over the waveguide substrate 201. In some embodiments, the slab waveguide layer 210 is disposed on a first surface 203 (i.e., top surface) or a second surface 205 (i.e., bottom surface) opposing the first surface 203 of the waveguide substrate 201.

[0023] In embodiments, shown in the first configuration 401, the grating structures 208, are disposed in the slab waveguide layer 210. In embodiments, shown in the third configuration 403 and the fourth configuration 404, the grating structures 208 are disposed over, and in some embodiments on, the slab waveguide layer 210. The grating structures 208 having a grating RI n_{grat}. A grating material 212 of the grating structures 208 resulting in the grating RI n_{grat}. In embodiments, of the second configuration 402, the grating structures 208 of the in-coupler 202 are disposed in the slab waveguide layer 210 and the grating structures 208 the first grating 204 and the second grating 206 are disposed over the slab waveguide layer 210.

[0024] The slab waveguide layer 210 include at least one slab depth d_{swg}. The first grating 204 has a first slab depth d_{swg1}. The second grating 204 has a second slab depth d_{swg2}. The slab depth d_{swg} corresponds to the first slab depth d_{swg1} or the second slab depth d_{swg2}. The slab depth d_{swg} is from a lower surface 209 to an upper surface 211 of the slab waveguide layer 210. The first slab depth d_{swg1} of the first configuration 401 is from the lower surface 209 to the upper surface 211 of the slab waveguide

layer 210 between grating structures 208 of the first grating 204. The second slab depth d_{swg2} of the first configuration 401 is from the lower surface 209 to the upper surface 211 the slab waveguide layer 210 between grating structures 208 of the second grating 206. In other embodiments, the first slab depth d_{swg1} is the thickness of the slab waveguide layer 210 under the first grating 204, i.e, the distance from the lower surface 209 to the upper surface 211. The second slab depth d_{swg2} is the thickness of the slab waveguide layer 210 under the second grating 206. The slab waveguide layer 210 has a slab refractive index (RI) n_{swg}. A superstrate 214 corresponds to region between and over the grating structures 208. In some embodiments, the superstrate 214 is air (refractive index of 1.0). In other embodiments, the superstrate 214 is a coating 504 as shown in Figure 4C. The superstrate 214 has a superstrate RI $n_{superstrate}$. The waveguide 200 has n_{swg} greater than $n_{superstrate}$, and n_{swg} greater than n_{sub}.

[0025] The waveguide substrate 201 may be formed from any suitable material, provided that the waveguide substrate 201 can adequately transmit light in a selected wavelength or wavelength range and can serve as an adequate support for the waveguide 100 described herein. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, and combinations thereof. In some embodiments, which may be combined with other embodiments described herein, the waveguide substrate 201 includes glass, silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), fused silica, quartz, sapphire (Al_2O_3), silicon carbide (SiC), lithium niobate ($LiNbO_3$), indium tin oxide (ITO), or combinations thereof. In other embodiments, which may be combined with other embodiments described herein, the waveguide substrate 201 includes high-refractive-index glass. The high-refractive-index glass includes greater than 2 percent by weight of lanthanide (Ln), titanium (Ti), tantalum (Ta), or combination thereof.

[0026] The slab waveguide layer 210 may include one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate

(Cd_2SnO_4), titanium silicon oxide (TiSiOx) or silicon carbon-nitride (SiCN) containing materials. The grating material 212 may include one or more of SiOC, TiO_2, SiO_2, VOx, Al_2O_3, AZO, ITO, SnO_2, ZnO, Ta_2O_5, Si_3N_4, ZrO_2, Nb_2O_5, Cd_2SnO_4, TiSiOx, or SiCN containing materials. In some embodiments, a slab waveguide material of the slab waveguide layer 210 and the grating material 212 are the same resulting in the same n_{grat} and n_{swg}. In other embodiments, the slab waveguide material of the slab waveguide layer 210 and the grating material 212 are different resulting in n_{grat} and n_{swg} that are different.

[0027] The blue, green, and red channel light will propagate in both the waveguide substrate 201 and slab waveguide layer 210 and will still experience a resonance condition as light can reflect off the superstrate and substrate interfaces. The superstrate RI $n_{superstrate}$, the slab refractive index RI n_{swg}, and the slab depth d_{swg}, such as the first slab depth d_{swg1} and the second slab depth d_{swg2} must be selected to reduce the ratio diffraction efficiency of the blue channel light to the red channel light.

[0028] The resonance condition of the substrate modes in the waveguide 200 will occur when the following condition is met:

$$2n_{swg}k_0\cos(\theta)d + \phi_{sub} + \phi_{grating} = 2\pi m$$

where n_{swg} is the slab refractive index RI n_{swg}, k_0 is the wavenumber of light ($2\pi/\lambda_0$), d is the slab depth d_{swg}, θ is the angle of propagation of light in the slab waveguide layer, ϕ_{sub} is the phase accumulated upon reflection at the slab waveguide-substrate interface 213, and $\phi_{grating}$ is the phase accumulated upon reflection at the slab waveguide-superstrate interface 213. The phases ϕ_{sub} and $\phi_{grating}$ can be calculated using the Fresnel equations.

[0029] The change in slab depth d_{swg} between resonance peaks, Δd, is determined by solving the above resonance condition according the following formula:

$$\Delta d = \frac{\lambda_0}{2n_{swg}\cos(\theta)}$$

Δd depends on both the wavelength (λ_0) and the angle of propagation (θ). λ_0 corresponds to the wavelengths of blue channel light (wavelengths of 380 nm to about

495 nm), green channel light (wavelength of about 495 nm to about 590 nm), and red channel light (wavelength of about 590 nm to about 750 nm).

[0030] The diffraction efficiency of the waveguide 200 is modeled via optical simulation. Optical simulation includes rigorous coupled-wave analysis (RCWA), finite-difference time-domain (FDTD) method, finite element method (FEM), other methods of simulation, and combinations thereof. The optimal the slab refractive index RI n_{swg} and the slab depth d_{swg} are selected via modeling.

[0031] Figure 3 is graph of simulated diffraction efficiency of three waveguides. The waveguide 100 simulated does not include the slab waveguide layer 210. The diffraction efficiency ratio is the ratio of the minimum diffraction efficiency of blue channel light to the maximum diffraction efficiency red channel light. The waveguide 100 described herein that is modeled has a diffraction efficiency DE_1 of 4.5:1.0 (18% minimum diffraction efficiency of blue channel light to 4% maximum diffraction efficiency red channel light). Wave 301A is the diffraction efficiency of blue channel light at a wavelength λ_0 of 450 nanometers (nm) for a first model of the waveguide 200. Wave 301B is the diffraction efficiency of green channel light at a wavelength λ_0 of 520 nm for the first model of the waveguide 200. Wave 301C is the diffraction efficiency of red channel light at a wavelength λ_0 of 620 nm for the first model of the waveguide 200. The first model of the waveguide 200 has a waveguide substrate 201 with a n_{sub} of 2.0 and a slab waveguide layer 210 of amorphous TiOx with an n_{swg} of 2.45 at 450 nm, 2.37 at 520nm, and 2.31 at 620nm. The first model of the waveguide 200 has a diffraction efficiency DE_2 of 1.8:1.0 at 50 nm. To improve the diffraction efficiency ratio, waveguide 200 is modeled a second time.

[0032] Wave 302A is the diffraction efficiency of blue channel light at a wavelength λ_0 of 450 nm for a second model of the waveguide 200. Wave 302B is the diffraction efficiency of green channel light at a wavelength λ_0 of 520 nm for a first model of the waveguide 200. Wave 302C is the diffraction efficiency of red channel light at a wavelength λ_0 of 620 nm for the third model of the waveguide 200. The second model of the waveguide 200 has a waveguide substrate 201 with an n_{sub} of 2.0 and a slab waveguide layer 210 of crystalline TiOx with an n_{swg} of 2.73 at 450 nm, 2.61 at 520nm, and 2.53 at 620nm. The average n_{swg} is 2.62. The second of the waveguide 200 has a diffraction efficiency DE_3 of 1.1:1.0 at 35 nm. Thus, the second model of the

waveguide 200 includes a n_{sub} of 2.0, average n_{swg} of 2.62, and slab depth d_{swg} of 35 nm.

[0033] In some embodiments, the substrate RI n_{sub} of the waveguide substrate at 620 nm is 1.8 to 2.10. In other embodiments, the substrate RI n_{sub} of the waveguide substrate at 620 nm greater than 2.77. Table 1 shows optimal ranges of slab depth d_{swg} based on a substrate RI n_{sub} of 2.0 and a respective slab RI n_{swg} at 620 nm.

Slab RI n_{swg} at 620 nm	**Optimal Range of Slab Depth d_{swg}**
2.1	75 nm – 110 nm
2.2	55 nm – 100 nm
2.3	35 nm – 85 nm
2.4	30 nm – 70 nm
2.5	25 nm – 60 nm
2.6	15 nm – 50 nm

Table 1

[0034] Figures 4A-4C are cross-sectional views of the waveguide 200 according to different configurations. In a second configuration 402 as shown in Figure 4A, the grating structures 208 of the in-coupler 202 are disposed in the slab waveguide layer 210 and the grating structures 208 the first grating 204 and the second grating 206 are disposed over the slab waveguide layer 210. A grating material 212 of the grating structures 208 over the slab waveguide layer 210 has a grating RI n_{grat}. In some embodiments, the slab waveguide layer 210 and the grating material 212 are the same resulting in the same n_{grat} and n_{swg}. In other embodiments, the slab waveguide layer 210 and the grating material 212 are different resulting in n_{grat} and n_{swg} that are different. The third configuration 403 as shown in Figure 4B and the fourth configuration 404 as shown in Figure 3C include the grating structures 208 are disposed over, and in some embodiments on, the slab waveguide layer 210. The fourth configuration 404 of the waveguide 200 include a second slab waveguide layer 410. The slab waveguide layer 210 and the second slab waveguide layer 410 are disposed on opposite sides of the waveguide substrate 201. The second slab waveguide layer 410 includes at least a third grating 407 disposed thereover. In some embodiments, a fourth grating 409 is disposed over the second slab waveguide layer 410.

[0035] Figures 5A-5E are cross-sectional views of gratings 500. The gratings 500 may correspond to at least one of the in-coupler 202, the first grating 204, or the second grating 206 of the waveguide 200. As shown in Figure 5A, the grating structures 208 are blazed grating structures. As shown in Figure 5B, the grating structures 208 have sidewalls 502 parallel to each other and angled relative to the first surface 203 of the waveguide substrate 201. As shown in Figure 5C, the grating structures 208 have sidewalls 502 parallel to each other and perpendicular to the first surface 203 of the waveguide substrate 201. The superstrate 214 is a coating 504. As shown in Figure 5D, the grating structures 208 include a first layer 506 of a first material and a second layer 508 of a second material. As shown in Figure 5E, the grating structures 208 the grating structures have two-dimensional periodicity.

[0036] While the foregoing is directed to examples of the present disclosure, other and further examples of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

CLAIMS

1. A waveguide, comprising:

a waveguide substrate;

a slab waveguide layer disposed over the waveguide substrate;

a grating material disposed on the slab waveguide layer, wherein a material of the slab waveguide layer and the grating material are different;

an incoupler grating defined by a first portion of a plurality of grating structures, the grating structures of the incoupler grating are disposed in the grating material and the slab waveguide layer such that the grating structures of the incoupler grating are at least disposed in a layer of the grating material; and

an outcoupler grating defined by a second portion of the plurality of grating structures, the grating structures of the outcoupler grating are at least disposed in the grating material on the slab waveguide layer, wherein:

the grating structures of the incoupler grating are blazed grating structures and the grating structures of the outcoupler grating have sidewalls parallel to each other.

2. The waveguide of claim 1, wherein a superstrate is over at least a portion of the grating structures.

3. The waveguide of claim 2, wherein:

the superstrate has a superstrate RI $n_{superstrate}$, wherein a slab RI n_{swg} of the slab waveguide layer is greater than a substrate RI n_{sub} of the waveguide substrate and the slab RI n_{swg} is greater than the superstrate RI $n_{superstrate}$.

4. The waveguide of claim 1, wherein the incoupler grating has a depth from a lower surface to an upper surface of the slab waveguide layer between the grating structures of the incoupler grating, and the slab waveguide layer has a slab depth d_{swg} from the lower surface to the upper surface of the slab waveguide layer between the

grating structures of the outcoupler grating, the slab depth d_{swg} is greater than the depth of the incoupler grating.

5. The waveguide of claim 1, wherein the grating structures of the incoupler grating are disposed in the layer of the grating material and a layer of the slab waveguide layer.

6. The waveguide of claim 1, wherein a coating is disposed between and on the grating structures of the incoupler grating.

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

the waveguide substrate has greater than 2 percent by weight of lanthanide (Ln), titanium (Ti), tantalum (Ta), or a combination thereof.

8. The waveguide of claim 1, wherein: the slab waveguide layer comprises one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate (Cd_2SnO_4), titanium silicon oxide (TiSiOx), or silicon carbon-nitride (SiCN) containing materials.

9. The waveguide of claim 1, wherein the grating material comprises one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate

(Cd_2SnO_4), titanium silicon oxide (TiSiOx), or silicon carbon-nitride (SiCN) containing materials.

10. The waveguide of claim 1, wherein the slab waveguide layer is disposed on the waveguide substrate.

11. The waveguide of claim 1, wherein the grating material comprises TiO_2 and the slab waveguide layer comprises Nb_2O_5.

12. The waveguide of claim 1, wherein a height of the grating structures of the outcoupler grating increases across the outcoupler grating.

13. A waveguide, comprising:

a waveguide substrate;

a slab waveguide layer disposed over the waveguide substrate, the slab waveguide layer;

a grating material disposed on the slab waveguide layer, wherein the grating material;

an incoupler grating defined by a first portion of a plurality of grating structures, the grating structures of the incoupler grating are disposed in the grating material and the slab waveguide layer such that the grating structures of the incoupler grating include a layer of the grating material and a layer of the slab waveguide layer; and

an outcoupler grating defined by a second portion of the plurality of grating structures, the grating structures of the outcoupler grating are at least disposed in the grating material.

14. The waveguide of claim 13, wherein a coating is disposed between and on the grating structures of the incoupler grating.

15. The waveguide of claim 13, wherein:

the grating structures of the incoupler grating are blazed grating structures and the grating structures of the outcoupler grating have sidewalls parallel to each other or have sidewalls parallel to each other and angled relative to a surface of the waveguide substrate.

16. The waveguide of claim 13, wherein the incoupler grating has a depth from a lower surface to an upper surface of the slab waveguide layer between the grating structures of the incoupler grating, and the slab waveguide layer has a slab depth d_{swg} from the lower surface to the upper surface of the slab waveguide layer between the grating structures of the outcoupler grating, the slab depth d_{swg} is greater than the depth of the incoupler grating.

17. The waveguide of claim 13, wherein the waveguide substrate comprises glass, silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), fused silica, quartz, sapphire (Al_2O_3), silicon carbide (SiC), lithium niobate ($LiNbO_3$), indium tin oxide (ITO), or combinations thereof; or

the waveguide substrate has greater than 2 percent by weight of lanthanide (Ln), titanium (Ti), tantalum (Ta), or a combination thereof.

18. A waveguide, comprising:

a waveguide substrate;

a slab waveguide layer disposed over the waveguide substrate, the slab waveguide layer comprises niobium oxide (Nb_2O_5);

a grating material disposed on the slab waveguide layer, wherein the grating material comprises titanium dioxide (TiO_2);

an incoupler grating defined by a first portion of a plurality of grating structures, the grating structures of the incoupler grating are disposed in the grating material and the slab waveguide layer such that the grating structures of the incoupler grating are at least disposed in a layer of the grating material; and

an outcoupler grating defined by a second portion of the plurality of grating structures, the grating structures of the outcoupler grating are at least disposed in the grating material on the slab waveguide layer, wherein:

the grating structures of the incoupler grating are blazed grating structures and the grating structures of the outcoupler grating have sidewalls parallel to each other.

19. The waveguide of claim 20, wherein the grating structures of the incoupler grating are disposed in the layer of the grating material of the grating material and a layer of the slab waveguide layer.

20. The waveguide of claim 20, wherein a coating is disposed between and on the grating structures of the incoupler grating.