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(54) WAVEGUIDE BONDING THROUGH BLACKENING INK

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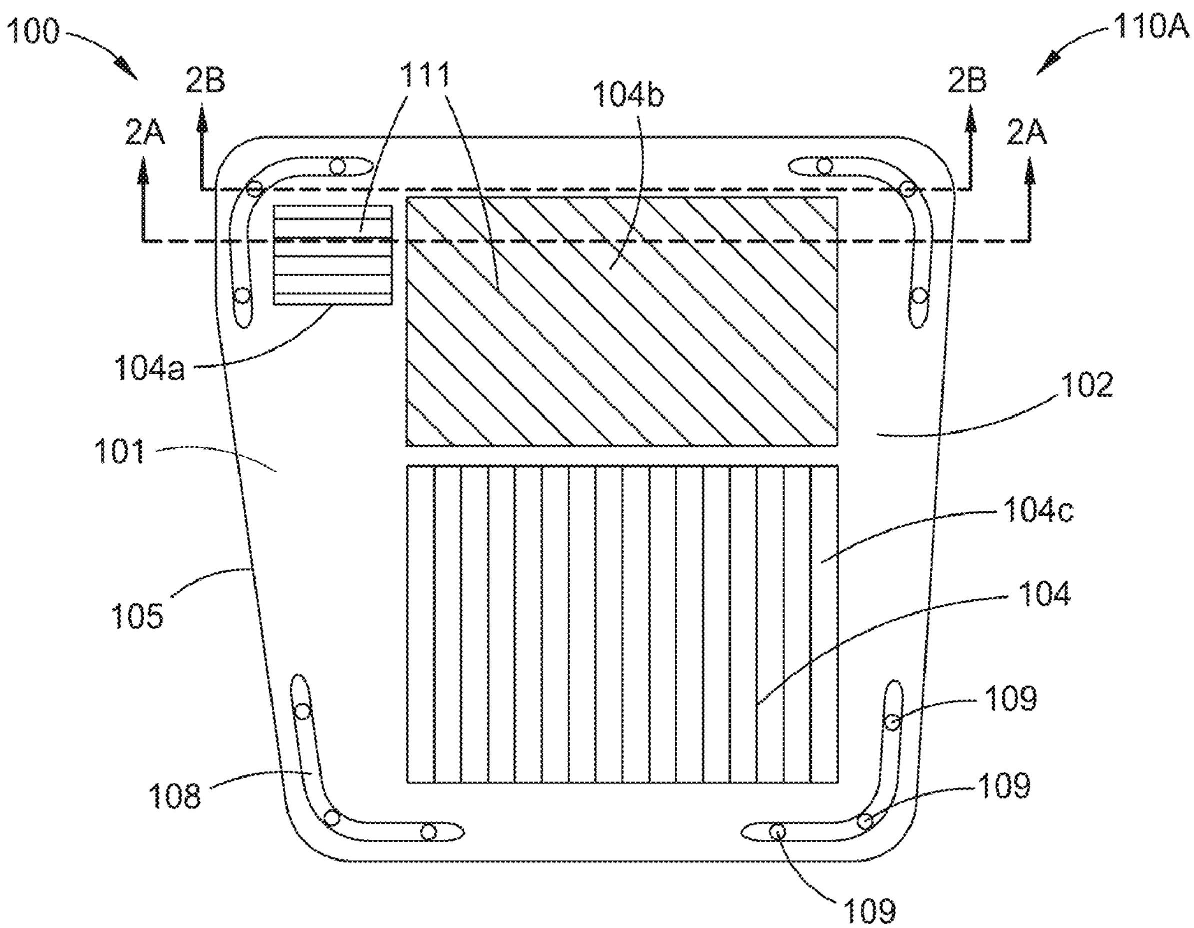
CPC *G02B 27/0176* (2013.01)

(57) **ABSTRACT**

Embodiments of the present disclosure generally relate to a device with a substrate with a first surface, a second surface, and an edge where the first surface of the substrate includes a waveguide, where the waveguide includes an input coupling grating, a pupil expansion grating, and an output coupling grating. The device additionally includes a cover substrate, a blackening section disposed over the first surface between the edge of the substrate and the waveguide, and a gap between the substrate and the cover substrate. A method includes disposing blackening material over the substrate, placing a cover substrate on the blackening material and curing to form a blackening section. Another method includes disposing blackening material over the substrate, curing the blackening material to form a blackening section, disposing adhesive over the blackening section, curing the adhesive, and placing a cover substrate on the adhesive.



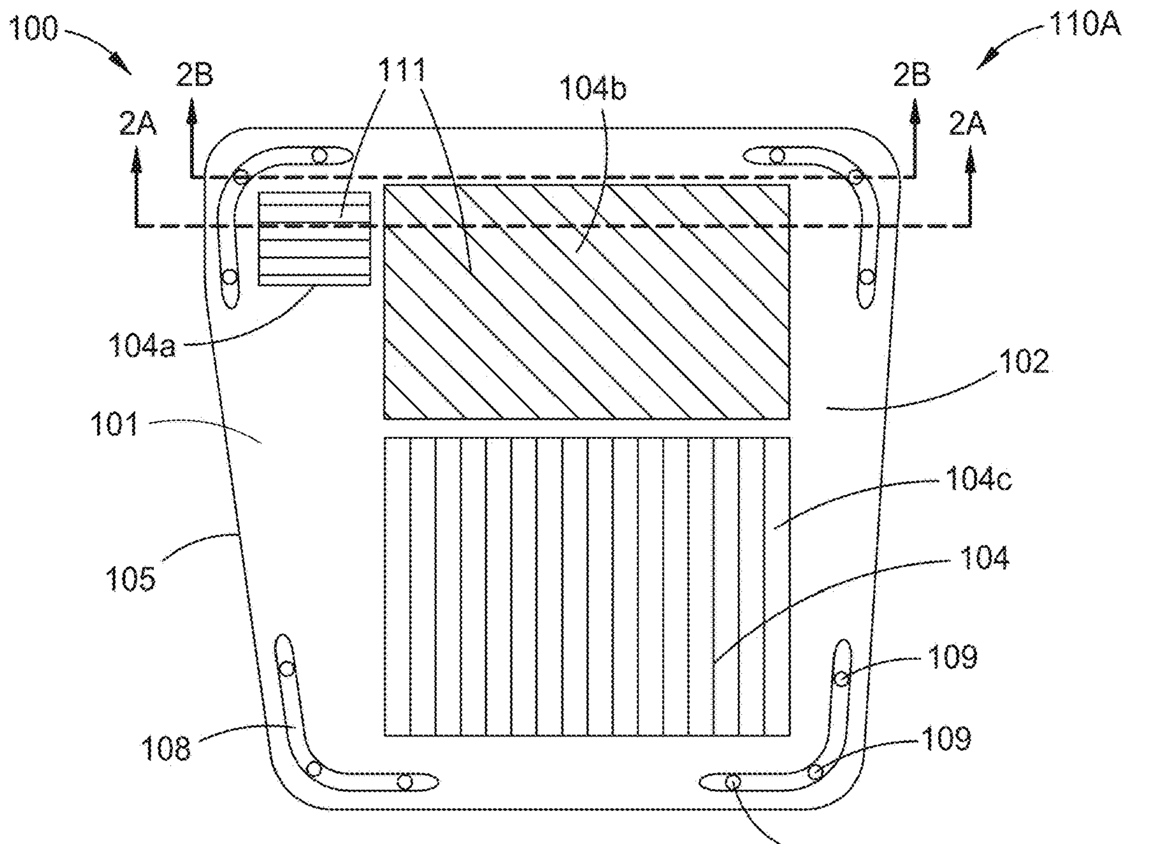

100
110A
2B
2B
2A
2A
111
104b
104a
101
102
104c
104
105
109
109
108
109

FIG. 1A

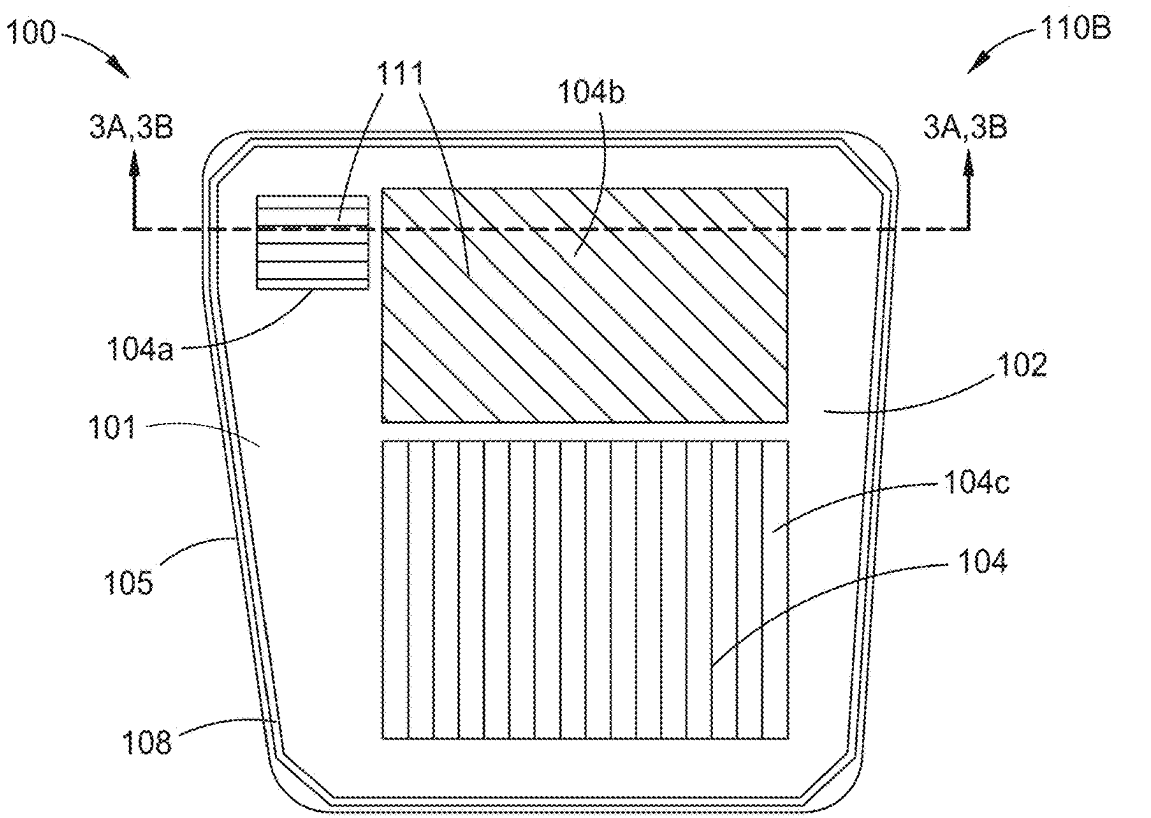

100
110B
111
104b
3A,3B
3A,3B
104a
101
102
104c
104
105
108

FIG. 1B

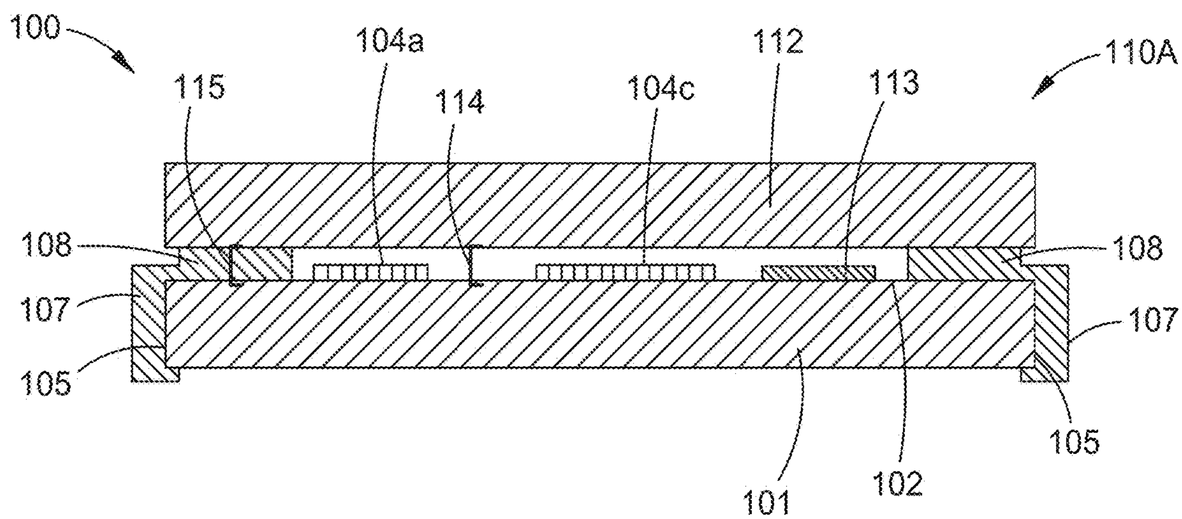

100
104a
112
110A
115
114
104c
113
108
108
107
107
105
105
101
102

FIG. 2A

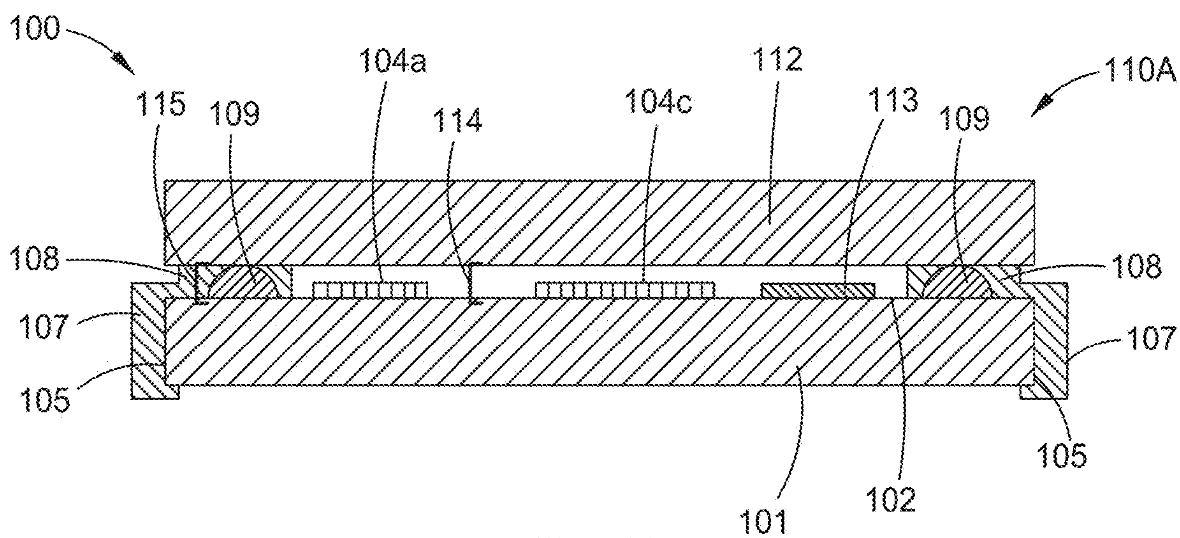

100
104a
112
110A
115
109
114
104c
113
109
108
108
107
107
105
105
101
102

FIG. 2B

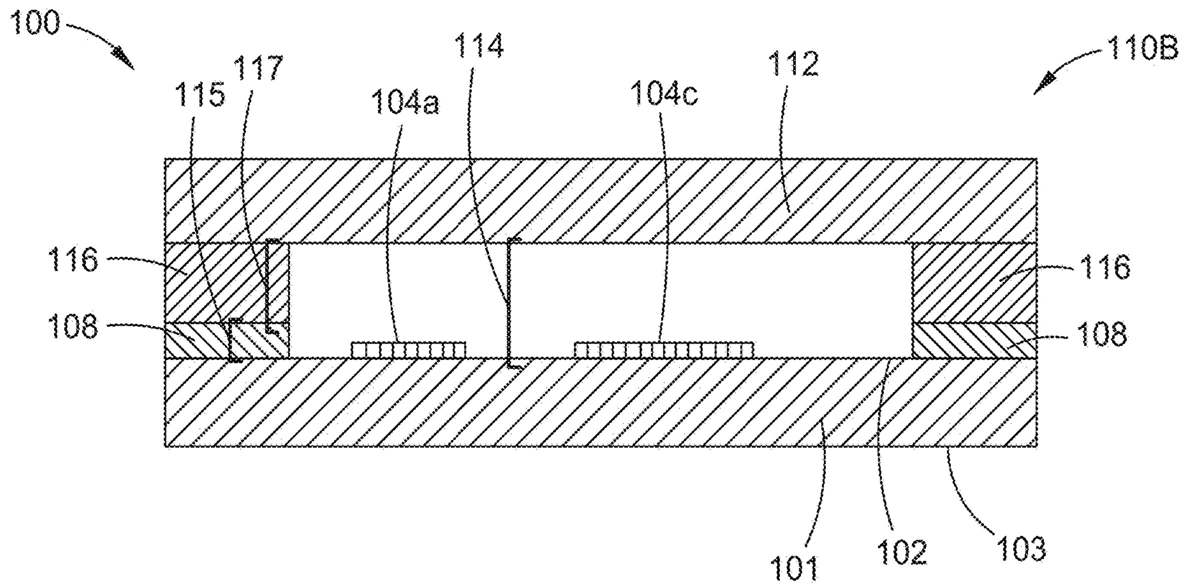

100
110B
115
117
114
112
104a
104c
116
116
108
108
101
102
103

FIG. 3A

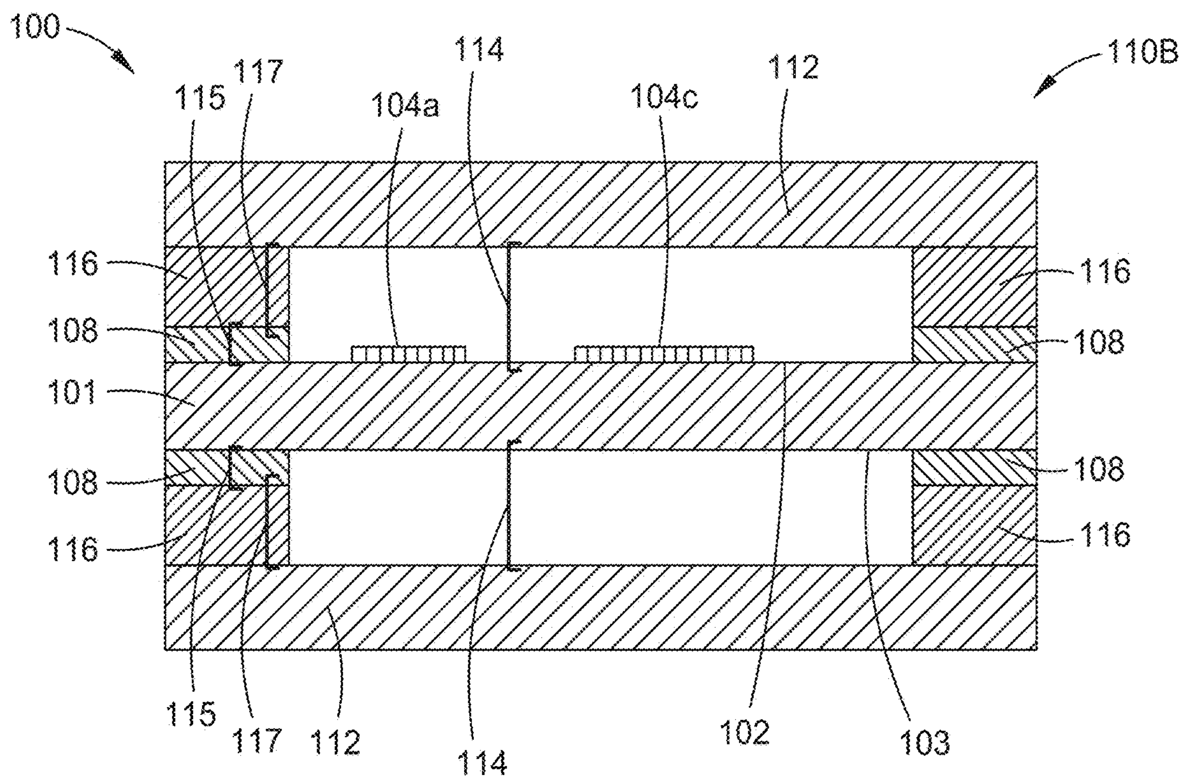

100
110B
115
117
114
112
104a
104c
116
116
108
108
101
108
108
116
116
115
117
112
114
102
103

FIG. 3B

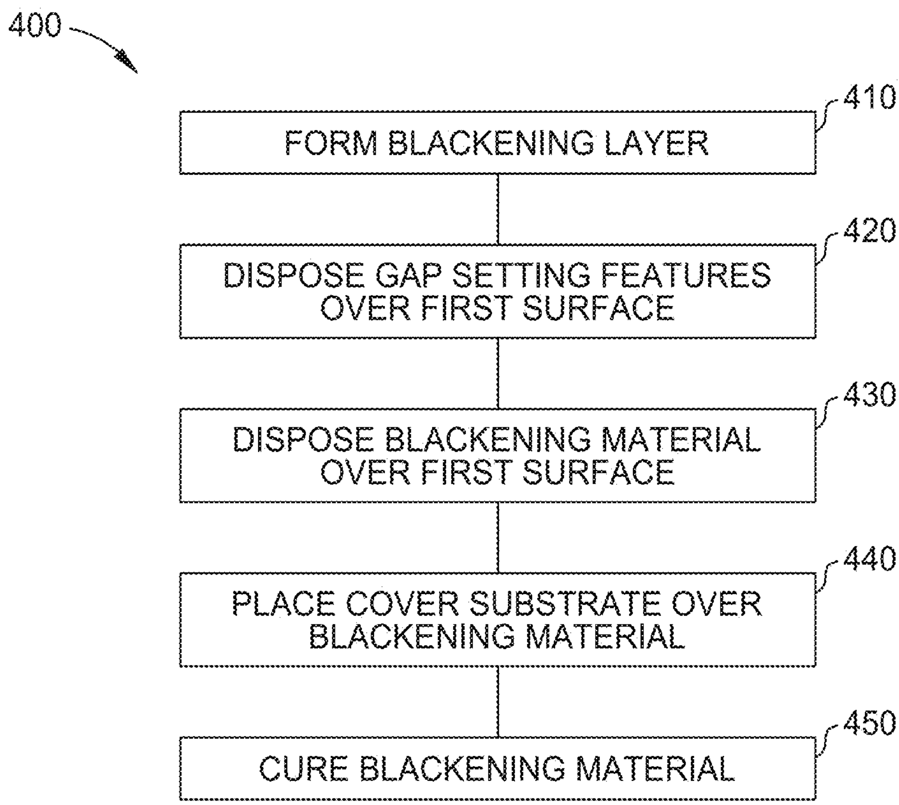

400
FORM BLACKENING LAYER
410
DISPOSE GAP SETTING FEATURES OVER FIRST SURFACE
420
DISPOSE BLACKENING MATERIAL OVER FIRST SURFACE
430
PLACE COVER SUBSTRATE OVER BLACKENING MATERIAL
440
CURE BLACKENING MATERIAL
450

FIG. 4

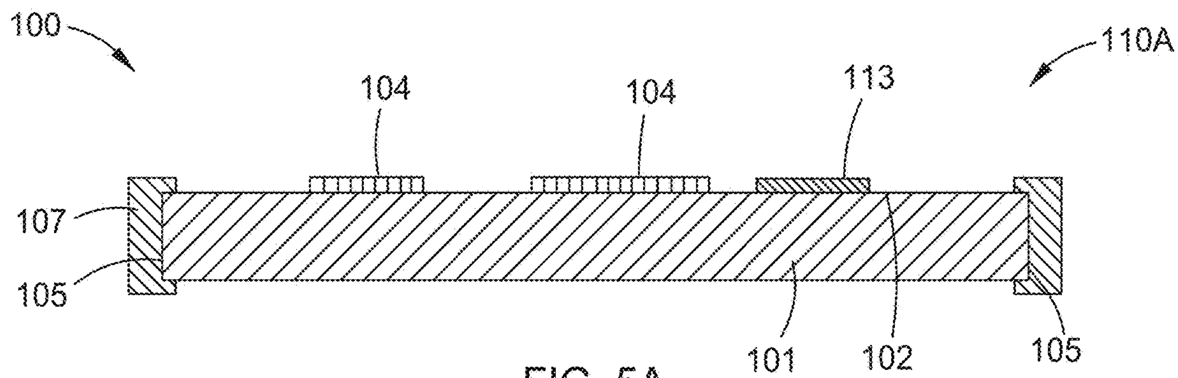


FIG. 5A

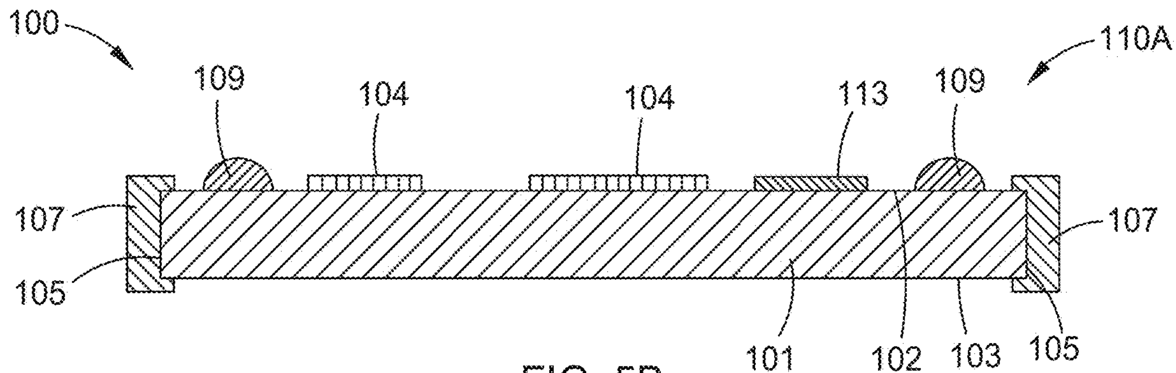


FIG. 5B

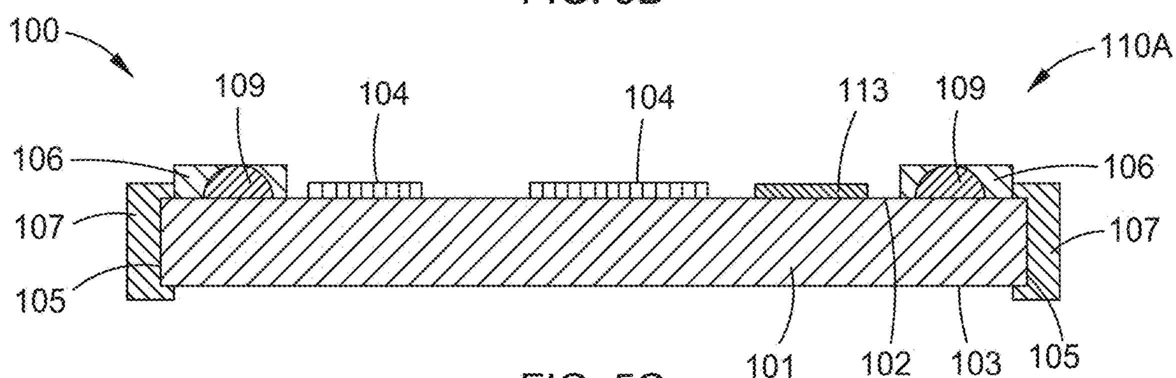


FIG. 5C

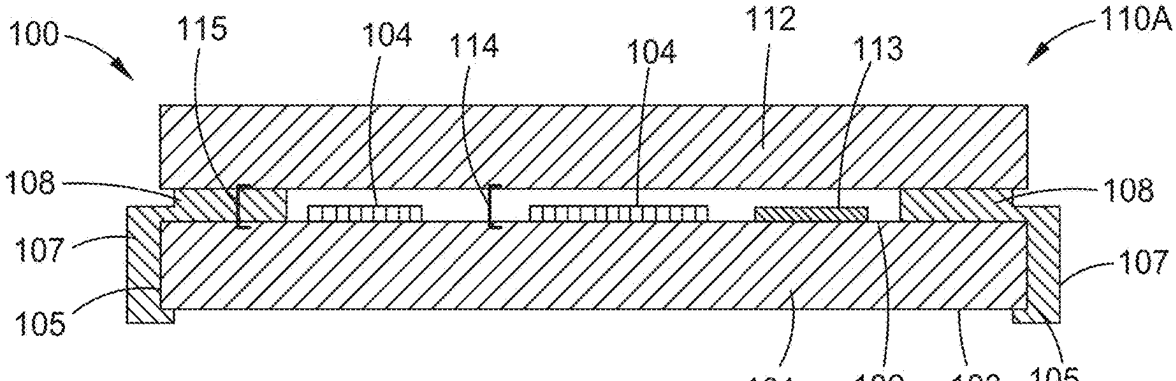


FIG. 5D

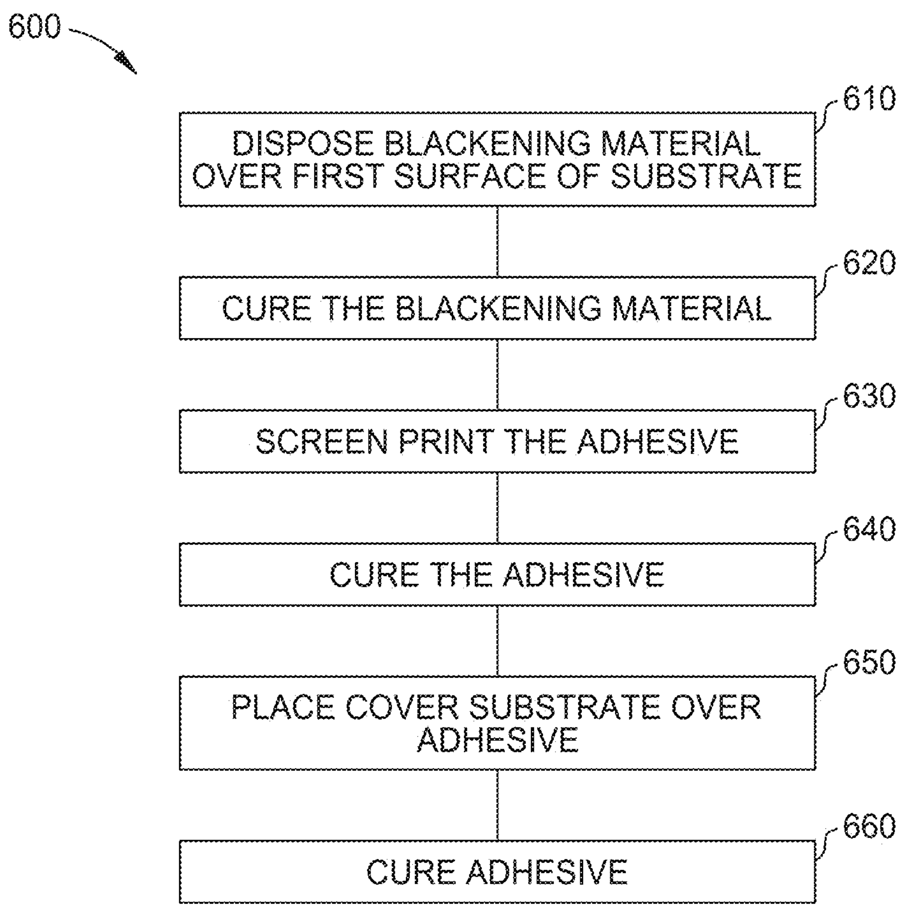

600
DISPOSE BLACKENING MATERIAL OVER FIRST SURFACE OF SUBSTRATE
610
CURE THE BLACKENING MATERIAL
620
SCREEN PRINT THE ADHESIVE
630
CURE THE ADHESIVE
640
PLACE COVER SUBSTRATE OVER ADHESIVE
650
CURE ADHESIVE
660

FIG. 6

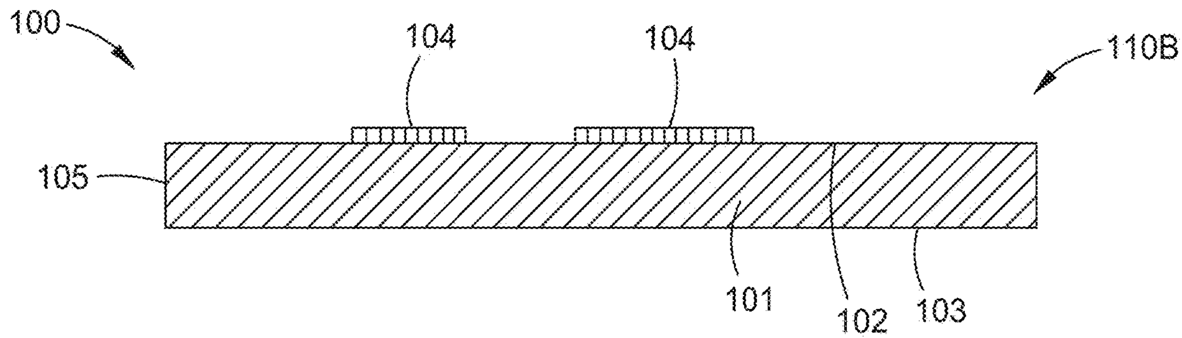


FIG. 7A

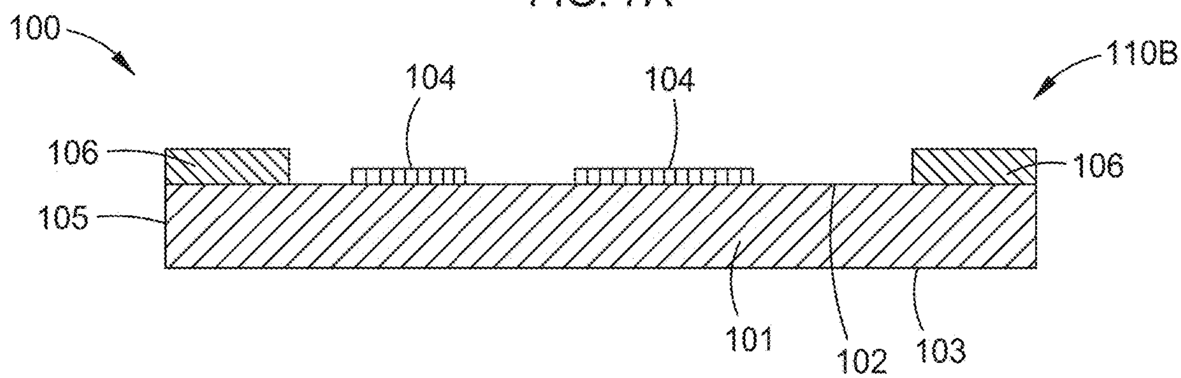


FIG. 7B

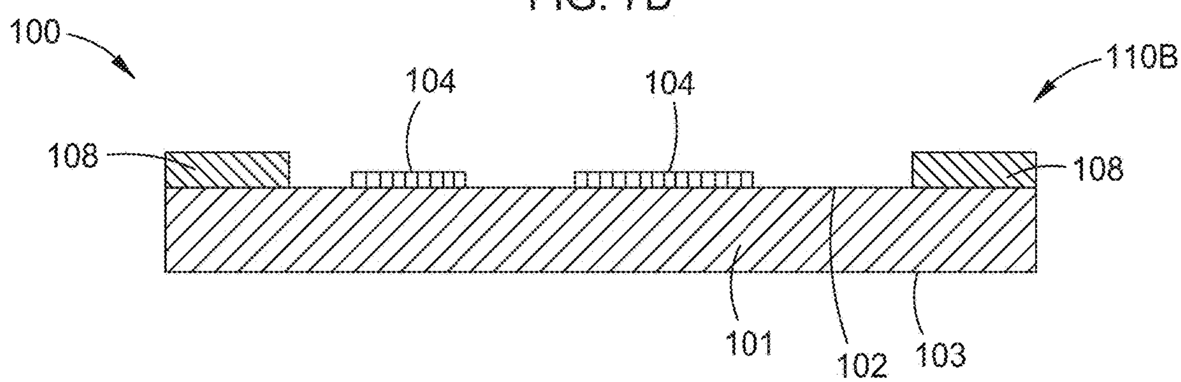


FIG. 7C

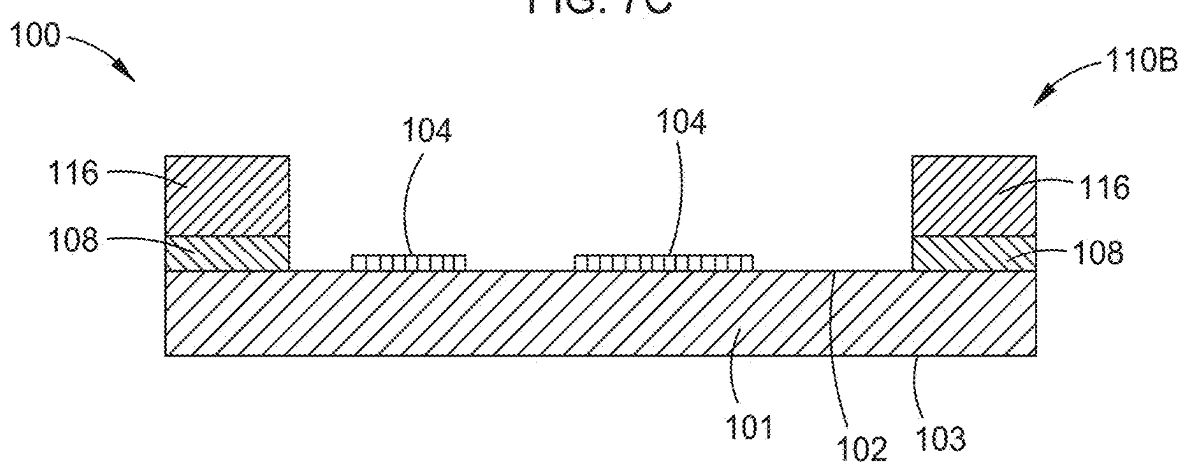


FIG. 7D

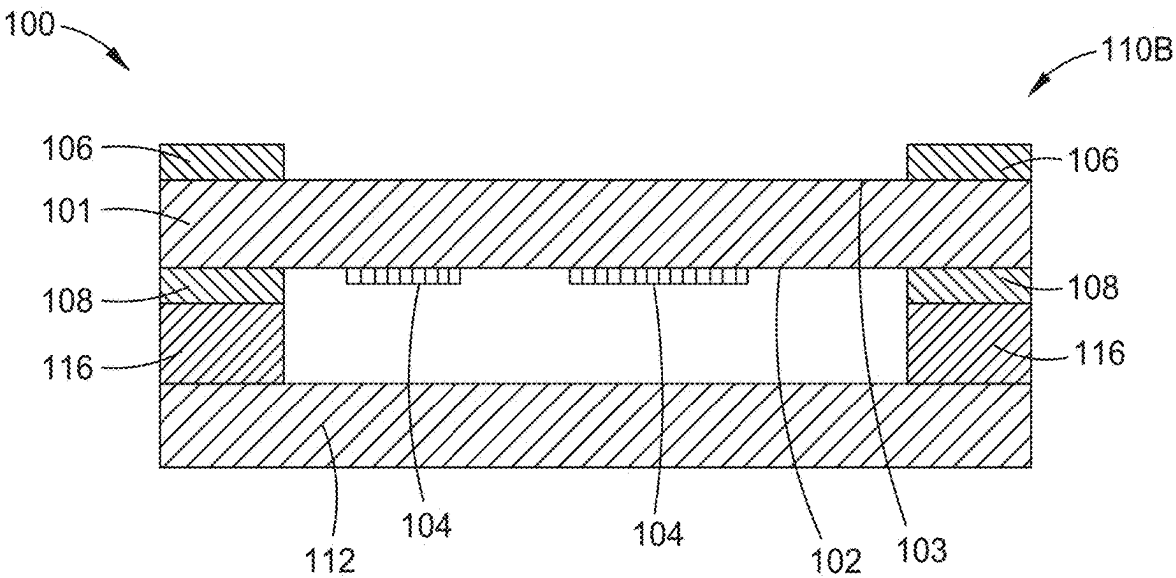
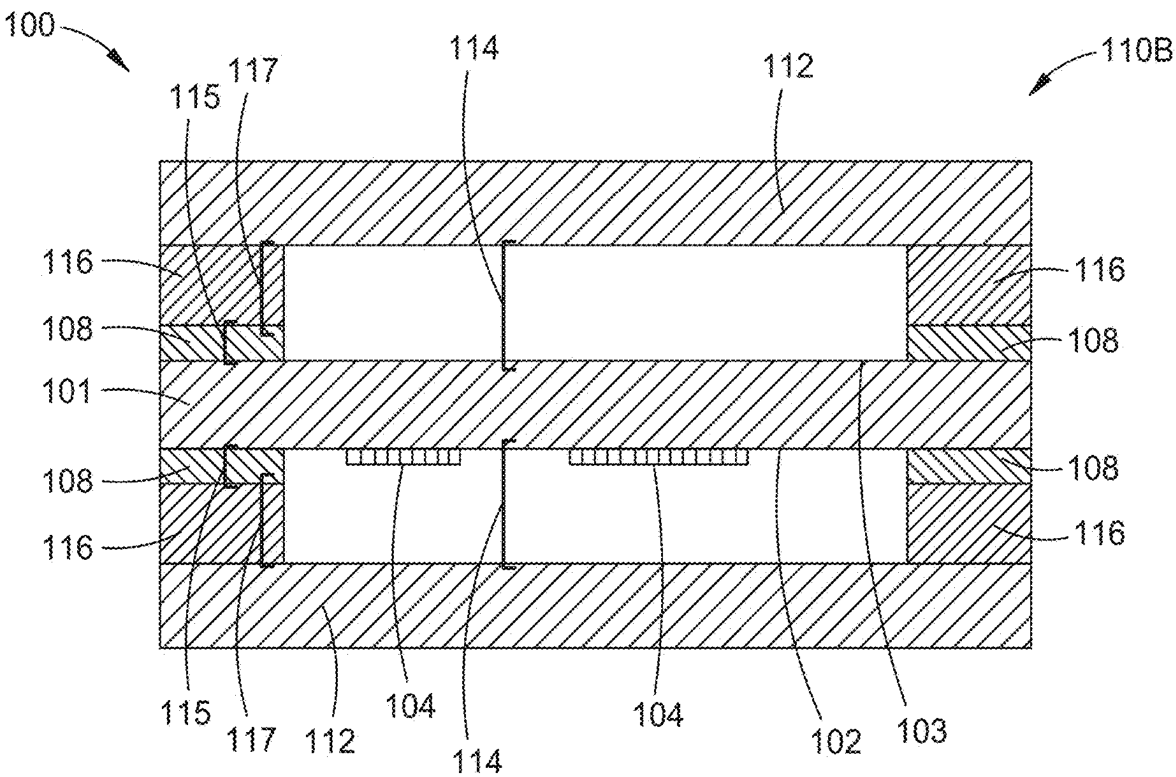

100
110B
106
106
101
108
108
116
116
112
104
104
102
103

FIG. 7E


100
110B
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117
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104
114
104
102
103

FIG. 7F

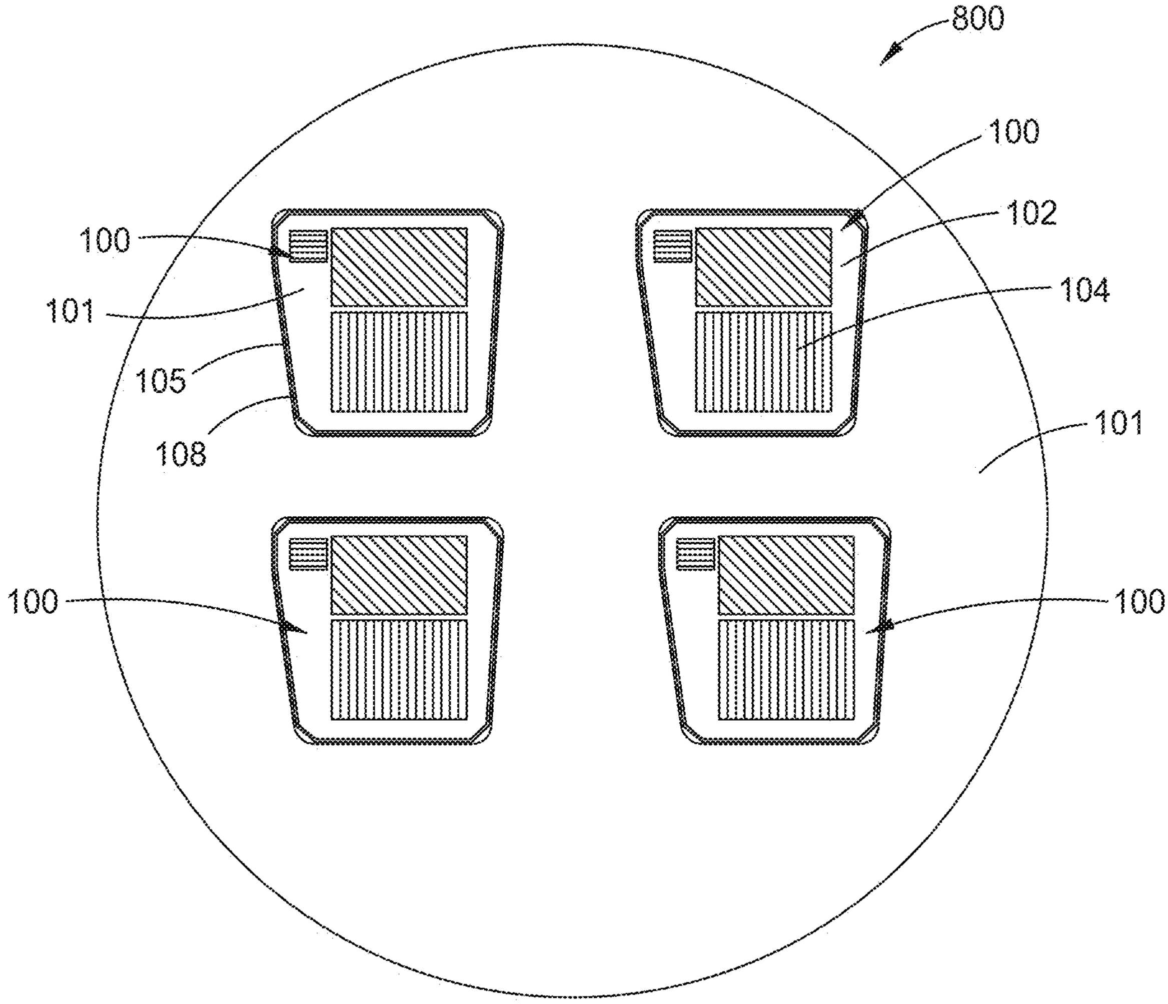

FIG. 8

WAVEGUIDE BONDING THROUGH BLACKENING INK

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/555,229, filed Feb. 19, 2024, which is incorporated by reference herein in its entirety.

BACKGROUND

Field

[0002] Embodiments of the present disclosure generally relate to waveguides. More specifically, embodiments described herein relate to a waveguide having a blackening section disposed over at least one surface and a method of forming the blackening section over the over at least one surface of the waveguide.

Description of the Related Art

[0003] 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.

[0004] 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.

[0005] Waveguides, such as augmented reality waveguides, are used to overlay virtual images over the ambient environment. Generated light is propagated through a waveguide until the light exits the waveguide and is overlaid on the ambient environment. A challenged occurs when light is propagated through the waveguide and exits the waveguide through the edge. The light exiting the waveguide at through the edge is visible to an external viewed. Another challenge occurs when a fraction of light bounces back into the waveguide after contact the edge of the optical device. The bounce back of light reduces the device performance. Waveguides may require coating one or more edges of the waveguide with a blackening material to prevent light bouncing back into the waveguide or exiting the waveguide through the edge.

[0006] Accordingly, what is needed in the art is a waveguide having at least one side partially coated with a blackening material and a method of disposing the blackening material over the waveguide.

SUMMARY

[0007] In one embodiment, a device is provided. The device includes a substrate with a first surface, a second surface and an edge where the first surface of the substrate includes a waveguide, where the waveguide includes an input coupling grating, a pupil expansion grating, and an output coupling grating. The device further includes a cover substrate, a blackening section disposed over the first surface of the substrate between the edge of the substrate and the waveguide, and a gap between the substrate and the cover substrate.

[0008] In another embodiment, a method is provided. The method includes forming a blackening layer on at least an edge of a substrate, the substrate having a first surface and a second surface, the first surface including a waveguide including at least one grating disposed over the first surface of the substrate, disposing blackening material over the first surface where the blackening material is disposed between the grating and the edge of the substrate, placing a cover substrate on the blackening material, and curing the blackening material to form a blackening section and bond the cover substrate to the blackening section.

[0009] In yet another embodiment, a method is provided. The method includes disposing blackening material over a first surface of a substrate, the substrate having a first surface and a second surface, wherein the first surface comprises a waveguide, the blackening material is disposed between a grating and the edge of the waveguide substrate, curing the blackening material to form a blackening section, disposing an adhesive over the blackening section, curing the adhesive, and placing a cover substrate on the adhesive.

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] FIGS. **1**A and **1**B are perspective, front views of a waveguide, according to certain embodiments.

[0012] FIGS. **2**A and **2**B are schematic, cross-sectional views, according to certain embodiments.

[0013] FIGS. **3**A and **3**B are schematic, cross-sectional view, according to certain embodiments.

[0014] FIG. **4** is a flow diagram of a method of fabricating a waveguide with a blackening layer configuration, according to certain embodiments.

[0015] FIGS. **5**A-**5**D are schematic, cross-sectional views of a substrate during fabrication of a waveguide with a blackening layer configuration, according to certain embodiments.

[0016] FIG. **6** is a flow diagram of a method of fabricating a waveguide with a blackening section configuration, according to certain embodiments.

[0017] FIGS. **7**A-**7**F are schematic, cross-sectional views of a substrate during fabrication of a waveguide with a blackening section configuration, according to certain embodiments.

[0018] FIG. **8** is a schematic, top view of a substrate during fabrication of a waveguide, according to certain embodiments.

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

DETAILED DESCRIPTION

[0020] Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to a waveguide having at least one surface partially coated with a blackening section and a method of disposing the blackening section over the waveguide. In some embodiments, blackening sections are disposed over portions of the surface and a blackening layer is disposed on the edge of the substrate. In other embodiments, a blackening section is disposed around the circumference of the surface.

[0021] FIGS. **1**A and **1**B are perspective, frontal views of a waveguide **100**. The waveguide **100** of FIG. **1**A corresponds to a blackening layer configuration **110**A further described herein. The waveguide **100** of FIG. **1**B corresponds to a blackening section configuration **110**B further described herein. It is to be understood that the waveguide **100** described herein is an exemplary waveguide and that other waveguides may be used with or modified to accomplish aspects of the present disclosure. The waveguide **100** includes a plurality of structures **111**. The structures **111** may be disposed over, under, or on a first surface **102** of a substrate **101**, or disposed in the substrate **101**. The structures **111** are nanostructures and have a sub-micron critical dimension, e.g., a width less than 1 micrometer. Regions of the structures **111** correspond to one or more gratings **104**. In one embodiment, which can be combined with other embodiments described herein, the waveguide **100** includes at least a first grating **104***a* corresponding to an input coupling grating and a third grating **104***c* corresponding to an output coupling grating. In another embodiment, which can be combined with other embodiments described herein, the waveguide **100** further includes a second grating **104***b*. The second grating **104***b* corresponds to a pupil expansion grating or a fold grating.

[0022] The substrate **101** may also be selected to transmit a suitable amount of light of a desired wavelength or wavelength range, such as one or more wavelengths from about 100 to about 3000 nanometers. Without limitation, in some embodiments, the substrate **101** is configured such that the substrate **101** transmits greater than or equal to about 50% to about 100%, of an infrared to ultraviolet region of the light spectrum. The substrate **101** may be formed from any suitable material, provided that the substrate **101** can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the waveguide **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 **101** includes a transparent material. In one embodiment, which may be combined with other embodiments described herein, the substrate **101** is transparent with absorption coefficient smaller than 0.001. Suitable examples may include silicon (Si), silicon dioxide (SiO_2), fused silica, quartz, silicon carbide (SiC), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), sapphire, lithium tantalate ($LiTaO_3$), lithium niobate ($LiNbO_3$), or combinations thereof. In some embodiments, which may be combined with other embodiments described herein, the substrate **101** has a substrate refractive index greater than 1.4, such as greater than 1.6, such as about 1.8, or about 2.0. In some embodiments, the refractive index of the blackening material **106** is less than about 40% of the refractive index of the substrate **101**. In some embodiments, the substrate refractive index and the blackening refractive index are substantially the same. In some embodiments, the substrate refractive index and the blackening refractive index are substantially the same.

[0023] In some embodiments, the structures **111** are disposed in the substrate **101**. In other embodiments, the structures **111** are disposed on or over the substrate **101**. In these embodiments, the structures **111** include a device material. The device material includes, but is not limited to, silicon carbide (SiC), 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), silicon mononitride (SIN), silicon oxynitride (SiON), barium titanate ($BaTiO_3$), diamond like carbon (DLC), hafnium (IV) oxide (HfO_2), lithium niobate ($LiNbO_3$), silicon carbon-nitride (SiCN), or combinations thereof.

[0024] In operation of the waveguide **100** a virtual image is projected from a near-eye display, such as a microdisplay, to the first grating **104***a*. The structures **111** of the first grating **104***a* in-couple the incident beams of light of the virtual image and diffract the incident beams to the second grating **104***b*. The diffracted beams undergo total-internal-reflection (TIR) until through the waveguide **100** until the diffracted beams come in contact with structures **111** of the second grating **104***b*. The diffracted beams from the first grating **104***a* incident on the second grating **104***b* are split into a first portion beams refracted back or lost in the waveguide **100**, a second portion beams that undergo TIR in the second grating **104***b* until the second portion beams contact another structure of the plurality of structures **111** of the second grating **104***b*, and a third portion of beams that are coupled through the waveguide **100** to the third grating **104***c*. The beams of the second portion of beams that undergo TIR in the second grating **104***b* continue to contact structures of the plurality of structures until the either the intensity of the second portion of beams coupled through the waveguide **100** to the second grating **104***b* is depleted, or remaining second portion of beams propagating through the second grating **104***b* reach the end of the second grating **104***b*.

[0025] The beams pass through the waveguide **100** to the third grating **104***c* and undergo TIR in the waveguide **100** until the beams contact a structure of the plurality of gratings **104** of the third grating **104***c* where the beams are split into beams that are refracted back or lost in the waveguide **100**, beams that undergo TIR in the third grating **104***c* until the beams contact another structure of the plurality of gratings **104**, or beams that are out-coupled from the waveguide **100** to the user's eye. The beams that undergo TIR in the third grating **104***c* continue to contact structures of the plurality of gratings **104** until the either the intensity of the beams pass through the waveguide **100** to the third grating **104***c* is depleted, or remaining beams propagating through the third grating **104***c* have reached the end of the third grating **104***c*. The beams of the virtual image are propagated from the third grating **104***c* to overlay the virtual image over the ambient environment.

[0026] Some light provided to the waveguide **100** strays from the intended path discussed above. For example, in some instances, a fraction of beams, i.e., stray light, reaches an edge **105** of the waveguide **100**. Upon reaching the edge **105**, the stray light can then be transmitted through the edge **105**, reflected, or scattered, through the waveguide **100** at a variety of angles, or absorbed at the edge **105**. Stray light that is transmitted through the edge **105** and/or stray light bounces from the edge **105** back through the waveguide **100** reduce the quality of virtual image via noise from the stray light. To reduce the amount of stray light transmitted through the edge **105** and the amount of stray light scattered in the waveguide **100** by the edge **105** the waveguide **100** includes a blackening layer configuration **110**A or a blackening section configuration **110**B. The blackening layer **107** prevents light from bouncing back into the waveguide **100** after hitting the edge **105**. If light bounces back into the waveguide **100** it will negatively affect the performance of the waveguide **100** because it causes a low contrast. The blackening layer **107** improves performance by having a refractive index as close to the refractive index that is substantially similar to the substrate refractive index. The light will leave the waveguide **100** and enter the blackening layer **107** because there is no optical discontinuity between the two materials. Additionally, the blackening layer **107** acts to absorb the light, which prevents the light from bouncing back into the waveguide **100**. The blackening layer configuration **110**A of the waveguide **100** includes blackening sections **108** of blackening material **106** disposed over portions of at least the first surface **102** and a blackening layer **107** of the blackening material **106** disposed on the edge **105** of the substrate **101**. The blackening section configuration **110**B of the waveguide **100** includes a blackening section **108** that is disposed on at least a first surface **102** of the substrate **101** or the circumference of the substrate **101**.

[0027] The blackening material **106** forms a blackening layer **107** on at least the edge **105** of the substrate **101**. Blackening material **106** is disposed on the first surface **102** of the substrate **101**. The blackening material **106**, when cured, forms a blackening section **108**. The blackening section **108** provides further assistance in reducing stray light transmitted through the waveguide. The blackening section **108** captures stray light as it bounces at different angels within the waveguide **100**. Stray light is captured wherever a blackening section **106** has been applied on a first surface **102**, or in some embodiments on the first surface **102** and the second surface **103**.

[0028] The blackening material **106** of the blackening section **108** and the blackening layer **107** has a refractive index that is substantially similar to the refractive index of the substrate. In some embodiments, which may be combined with other embodiments described herein, the substrate **101** has a substrate refractive index greater than 1.4, such as greater than 1.6, such as about 1.8, or about 2.0. In some embodiments, the refractive index of the blackening material **106** is less than about 40% of the refractive index of the substrate **101**. In some embodiments, the substrate refractive index and the blackening refractive index are substantially the same.

[0029] To obtain the blackening refractive index, the blackening material **106** includes a blacking ink, a siloxane-containing resin, or combinations thereof. The blackening material **106** includes, but is not limited to, one or more dyes, one or more pigments, a polymer mix of one or more binders, or combinations thereof. The blackening material **106** may further include one or more filler dispersions, one or more photoinitiator, one or more epoxy resin, one or more additives, one or more silanes, one or more isocyanates, one or more acids, one or more phosphine oxides, or combinations thereof.

[0030] FIGS. **2**A and **2**B are schematic, cross-sectional views of a waveguide **100**. The waveguide **100** of FIGS. **2**A and **2**B has blackening layer configuration **110**A. FIG. **2**A is a cross-section along line **2**A-**2**A as shown in FIG. **1**A. FIG. **2**B is a cross-section along line **2**B-**2**B shown in FIG. **1**A. As shown in FIG. **2**A, the blackening section **108** is disposed over the first surface **102** between the gratings **104** and the edge **105** of the substrate **101**. The blackening layer **107** is disposed on at least the edge **105** of the substrate **101**. The blackening section **108** is disposed on the first surface **102** and contacts the blackening layer **107**. In some embodiments, the blackening section **108** is disposed on the second surface **103** of the substrate **101**. The blackening section **108** and the blackening layer **107** reduce the amount of stray light transmitted through the edge **105** or peripheral of the first surface **102** and the amount of stray light scattered back into the waveguide **100** from the edge **105** or peripheral of the first surface **102**. A cover substrate **112** is coupled to the blackening section **108**. A space **114** is defined by the blackening section **108**, the cover substrate **112**, and the first surface **102** of the substrate **101**. The thickness **115** of the blackening section **108** provides for the size of the space **114**. The composition of the space **114** includes air having a refractive index of 1.0 and an absorption coefficient of 0. A mirror coating **113** is disposed on the first surface **102** of the substrate **101**. The mirror may be disposed between one of the gratings **104** and the blackening section **108**.

[0031] As shown in FIG. **2**B, the blackening material **106** is disposed over gap setting features **109**. A gap setting feature **109** may be a pressure sensitive adhesive or a glue. At least one gap setting feature **109** is disposed over the first surface **102** of the substrate **101** between the edge **105** of the substrate and at least one of the gratings **104**. The blackening material **106** surrounds the gap setting features **109**. The thickness **115** of the blackening material **106** is the same as the height of the gap setting features **109**. The blackening material **106** is soaked into the gap setting features **109** such that the blackening material **106** and the gap setting features **109**, once cured, form a single blackening section **108**. A cover substrate **112** is coupled to the blackening section **108**. A space **114** is defined by the blackening section **108**, the cover substrate **112**, and the first surface **102** of the substrate **101**. The thickness **115** of the blackening section **108** provides for the size of the space **114**. The composition of the space **114** includes air having a refractive index of less than 1.0 and an absorption coefficient of 0. A space **114** is desirable to prevent undesirable optical effects such as interference. The space **114** between the cover substrate **112** and the substrate **101** has a height of less than or equal to about 0.20, or about 0.15 mm, or about 0.10, or about 0.030 mm, or about 0.050 mm, or about 0.0025 mm.

[0032] FIGS. **3**A and **3**B are schematic, cross-sectional views of a waveguide **100**. The waveguide **100** of FIGS. **3**A and **3**B has blackening section configuration **110**B. FIG. **3**A and FIG. **3**B are cross-sections along line **3**A,**3**B-**3**A,**3**B, as shown in FIG. **1**B. As seen in FIG. **3**A, the blackening section **108** is disposed over the first surface **102** of the substrate **101** between the gratings **104** and the edge **105** of the substrate **101**. An adhesive **116** is disposed over the blackening section **108**. The adhesive **116** may be a pressure sensitive adhesive or a glue. A cover substrate **112** is coupled to the adhesive **116**. A space **114** is defined by the blackening section **108**, the adhesive **116**, the substrate **101**, and the cover substrate **112**. The thickness **115** of the blackening section **108** and the adhesive **116** provides the size of the space **114**. The composition of the space **114** includes air having a refractive index of less than 1.4 and an absorption coefficient of 0. A space **114** is desirable to prevent undesirable optical effects such as interference. The space **114** between the cover substrate **112** and the substrate **101** has a height of less than or equal to 0.1 mm, such as less than 0.050 mm, such as about 0.030 mm, about 0.020 mm or about 0.0025 mm.

[0033] As show in FIG. **3**B, the blackening section **108** is disposed over the first surface **102** of the substrate **101** between the gratings **104** and the edge **105** of the substrate **101** and the second surface **103** of the substrate **101**. An adhesive **116** is disposed over the blackening section **108** on the first surface **102** of the substrate **101** and the second surface **103** of the substrate **101**. A cover substrate **112** is coupled to the adhesive **116** on the first surface **102** and the second surface **103** of the substrate **101**. A space **114** is defined by the blackening section **108**, the adhesive **116**, the substrate **101**, and the cover substrate **112** on both the first surface **102** and the second surface **103** of the substrate. The thickness **115** of the blackening section **108** and the thickness **117** of the adhesive **116** provides the size of the space **114**. The thickness **115** of the blackening section **108** and the thickness **117** of the adhesive **116** is substantially similar on the first surface **102** and the second surface **103** of the substrate. The composition of the space **114** includes air having a refractive index of less than 1.4 and an absorption coefficient of 0. A space **114** is desirable to prevent undesirable optical effects such as interference. The space **114** between the cover substrate **112** and the substrate **101** has a height of less than or equal to 0.1 mm, such as less than 0.050 mm, such as about 0.030 mm, about 0.020 mm or about 0.0025.

[0034] FIG. **4** is a flow diagram of a method **400** of fabricating a waveguide **100** with a blackening layer **107** and a blackening section **108**. FIGS. **5**A-**5**E are cross-sectional views of a substrate **101** during fabrication of a waveguide with a blackening layer configuration **110**A according to embodiments. In one or more embodiments, a plurality of waveguides **800** (e.g., more than one waveguide **100**) are formed on the substrate **101**, as shown in FIG. **8**. The plurality of waveguides **800** are fabricated according to operation **420**, **430**, **440**, and **450** of method **400** on the substrate **101**. After operation **450**, the plurality of waveguides **800** formed on the substrate **101** are singulated into one or more individual waveguides **100** (e.g., each waveguide **100** is cut and removed from the substrate **101**). After singulation, a blackening layer **107** is formed on the edge **105** substrate **101** (e.g., on the edge **105** of the substrate **101** that was singulated where each substrate **101** includes a waveguide **100**) to form the waveguide **100** as shown in FIG. **5**E.

[0035] At operation **410**, a blackening layer **107** is formed on a substrate **101**. For example, as shown in FIG. **5**A, the blackening layer **107** is formed on an edge **105** of the substrate **101**. To form the blackening layer **107**, the blackening material **106** is disposed on at least the first surface **102** of the substrate **101**. The blackening material **106** is then cured to for the blackening layer **107**. The blackening material **106** may be cured via UV curing. The blackening layer **107** is cured, so that it forms a hardened layer around the edge **105** of the substrate **101**.

[0036] The blackening material includes a blacking ink, a siloxane-containing resin, or combinations thereof. The blackening material **106** additionally may include, but is not limited to, or more dyes, one or more pigments, a polymer mix of one or more binders, or combinations thereof. The blackening material **106** may further include one or more filler dispersions, one or more photoinitiator, one or more epoxy resin, one or more additives, one or more silanes, one or more isocyanates, one or more acids, one or more phosphine oxides, or combinations thereof. The blackening material **106** of the blackening section **108** and the blackening layer **107** has a refractive index that is substantially similar to the refractive index of the substrate. In some embodiments, which may be combined with other embodiments described herein, the substrate **101** has a substrate refractive index greater than 1.4, such as greater than 1.6, such as about 1.8, or about 2.0. In some embodiments, the refractive index of the blackening material **106** is less than about 40% of the refractive index of the substrate **101**. In some embodiments, the substrate refractive index and the blackening refractive index are substantially the same.

[0037] In a first optional operation, a mirror coating **113** is disposed on the first surface **102** of the substrate **101** by a FEOL process step. The mirror coating **113** may be disposed between one of the gratings **104** and the blackening section **108** to be formed.

[0038] At an optional operation **420**, gap setting features **109** are disposed on the first surface **102** of the substrate **101**. The gap setting features **109** are hard cured by a UV or thermal curing process.

[0039] At operation **430** a blackening material **106** is disposed over the first surface **102** of the substrate **101**, as shown in FIG. **5**C. The blackening material **106** used to create the blackening layer **107** is substantially the same as the blackening material disposed over the at least the first surface **102** of the substrate **101**. The blackening material **106** is disposed by screen printing, dispensing or inkjet printing over the substrate **101**. In some embodiments, the blackening section **108** is disposed on the second surface **103** of the substrate **101**. The blackening layer **107** prevents light from bouncing back into the waveguide **100** after hitting the edge **105**. If light bounces back into the waveguide **100** it will negatively affect the performance of the waveguide **100** because it causes a low contrast. The blackening layer **107** improves performance by having a refractive index as close to the refractive index that is substantially similar to the refractive index of the substrate **101**. The light will leave the waveguide **100** and enter the blackening layer **107** because there is no optical discontinuity between the two materials. Additionally, the blackening layer **107** acts to absorb the light, which prevents the light from bouncing back into the waveguide **100**. The blackening section **108** captures stray light as it bounces at different angels within the waveguide **100**. Stray light is captured wherever a blackening section **106** has been applied on a first surface **102**, or in some embodiments on the first surface **102** and the second surface **103**.

[0040] In another embodiment, including the gap setting features **109**, the blackening material **106** is disposed over the gap setting features **109**. The blackening material **106** is soaked into the gap setting features **109** such that the blackening material **106** and the gap setting features **109**, once cured, form a single blackening section **108**, as seen in FIG. **5**D.

[0041] At operation **440**, a cover substrate **112** is disposed over the blackening material **106**, as shown in FIG. **5**D. At operation **450**, the blackening material **106** is cured to bond the cover substrate **101** to the blackening section **108**, as shown in FIG. **5**D. When cured, the blackening material **106** creates a blackening section **108**. The blackening section **108** contacts the blackening layer **107**. The gap setting features **109** may also contact the cover substrate **112**. The curing creates a laminate seal. A space **114** is defined by the blackening section **108**, the cover substrate **112**, and the first surface **102** of the substrate **101**. The thickness **115** of the blackening section **108** provides for the size of the space **114**. The thickness **115** of the blackening section **108** is defined by the height of the gap setting features **109** in embodiments including the gap setting features **109**. The composition of the space **114** includes air having a refractive index of less than 1.4 and an absorption coefficient of 0. A space **114** is desirable to prevent undesirable optical effects such as interference. The space **114** between the cover substrate **112** and the substrate **101** has a height of less than or equal to 0.1 mm, such as less than 0.050 mm, such as about 0.030 mm, about 0.020 mm or about 0.0025.

[0042] FIG. **6** is a flow diagram of a method **600** of fabricating a waveguide **100** with a blackening section configuration **110**B. FIGS. **7**A-**7**F are cross-sectional views of a substrate during fabrication of a waveguide with a blackening section configuration **110**B according to embodiments. At operation **610**, blackening material **106** is disposed over a substrate **101**. The blackening material includes a blacking ink, a siloxane-containing resin, or combinations thereof. The blackening material **106**, additionally, may include, but is not limited to, or more dyes, one or more pigments, a polymer mix of one or more binders, or combinations thereof. The blackening material **106** may further include one or more filler dispersions, one or more photoinitiator, one or more epoxy resin, one or more additives, one or more silanes, one or more isocyanates, one or more acids, one or more phosphine oxides, or combinations thereof. The blackening material **106** of the blackening section **108** includes a refractive index that is substantially similar to the refractive index of the substrate. In one or more embodiments, the waveguide **100** includes the blackening layer (e.g., the blackening layer shown in FIG. **5**A-**5**D). In some embodiments, which may be combined with other embodiments described herein, the substrate **101** has a substrate refractive index greater than 1.4, such as greater than 1.6, such as about 1.8, or about 2.0. In some embodiments, the refractive index of the blackening material **106** is less than about 40% of the refractive index of the substrate **101**. In some embodiments, the substrate refractive index and the blackening refractive index are substantially the same.

[0043] The substrate **101** includes a first surface **102**, a second surface **103** and at least one grating **104**, as seen in FIG. **7**A. The blackening material **106** is disposed over the first surface **102** of the substrate **101** between at least one of the gratings **104** and an edge **105** of the substrate **101**, as seen in FIG. **7**B. The blackening material **106** is disposed by screen printing or inkjet printing.

[0044] At operation **620**, the blackening material **106** is cured by a UV or thermal process to create a blackening section **108**, as seen in FIG. **7**C. The blackening section **108** improves performance by having a refractive index as close to the refractive index that is substantially similar to the refractive index of the substrate **101**. The light will leave the waveguide **100** and enter the blackening section **108** because there is no optical discontinuity between the two materials. Additionally, the blackening section **108** acts to absorb the light, which prevents the light from bouncing back into the waveguide **100**.

[0045] At operation **630**, an adhesive **116** is disposed over the blackening section **108**, as seen in FIG. **7**D. The adhesive **116** is disposed over the blackening section **108** by screen printing. In one or more embodiments, at operation **640**, the adhesive **116** is cured. In one or more embodiments, the adhesive **116** is cured by a UV, a thermal curing process, or any other reasonable means of curing. At operation **650** a cover substrate **112** is placed over the adhesive **116**, as seen in FIG. **7**E. In embodiments where the adhesive **116** is a pressure sensitive adhesive, the cover substrate **112** is pressed slightly on the adhesive **116**. The pressure activates the adhesive **116** to form a bond between the blackening section **108** and the cover substrate **112**. In embodiments where the adhesive **116** is a glue, a gap setting feature **109** may be used to maintain the defined space **114** between the substrate **101** and the cover substrate **112**. A space **114** is defined by the blackening section **108**, the adhesive **116**, the substrate **101**, and the cover substrate **112** on both the first surface **102** and the second surface **103** of the substrate. The thickness **115** of the blackening section **108** and the thickness **117** of the adhesive **116** provides the size of the space **114**. The thickness **115** of the blackening section **108** and the thickness **117** of the adhesive **116** is substantially similar on the first surface **102** and the second surface **103** of the substrate. The composition of the space **114** includes air having a refractive index of less than 1.4 and an absorption coefficient of 0. A space **114** is desirable to prevent undesirable optical effects such as interference. The space **114** between the cover substrate **112** and the substrate **101** has a height of less than or equal to 0.1 mm, such as less than 0.050 mm, such as about 0.1 mm, such as about 0.030 mm, about 0.020 mm or about 0.0025. In one or more embodiments, at operation **650**, the adhesive **116** is cured, such that the cover substrate **112** is secured to the blackening section **108** which secures the cover substrate **112** to the substrate **101**. In one or more embodiments, at operation **660**, the adhesive **116** is cured. In one or more embodiments, operation **660** is a first cure of the adhesive **116**. In one or more embodiments, operation **660** is a second cure of the adhesive **116**. In one or more embodiments, the adhesive **116** is cured by a UV, a thermal curing process, or any other reasonable means of curing.

[0046] In some embodiments, method **600** is repeated on the second surface **103** of the substrate **101**, as seen in FIG.

7E. The blackening section **108** is disposed over the first surface **102** of the substrate **101** between the gratings **104** and the edge **105** of the substrate **101** and the second surface **103** of the substrate **101** by screen printing. An adhesive **116** is disposed over the blackening section **108** on the first surface **102** of the substrate **101** and the second surface **103** of the substrate **101** by screen printing. A cover substrate **112** is coupled to the adhesive **116** on the first surface **102** and the second surface **103** of the substrate **101**. A space **114** is defined by the blackening section **108**, the adhesive **116**, the substrate **101**, and the cover substrate **112** on both the first surface **102** and the second surface **103** of the substrate. The thickness **115** of the blackening section **108** and the thickness **117** of the adhesive **116** provides the size of the space **114**. The thickness **115** of the blackening section **108** and the thickness **117** of the adhesive **116** is substantially similar on the first surface **102** and the second surface **103** of the substrate. The composition of the space **114** includes air having a refractive index of less than 1.4 and an absorption coefficient of 0. A space **114** is desirable to prevent undesirable optical effects such as interference. The space **114** between the cover substrate **112** and the substrate **101** has a height of less than or equal to 0.1 mm, such as less than 0.050 mm, such as about 0.030 mm, about 0.020 mm or about 0.0025.

[0047] In one or more embodiments, a plurality of waveguides **800** (e.g., more than one waveguide **100**) are formed on the substrate **101**, as shown in FIG. **8**. The plurality of waveguides **800** are fabricated according to method **600** on the substrate **101**. After method **600**, the plurality of waveguides **800** disposed on the substrate **101** are singulated into one or more individual waveguides **100** (e.g., the waveguide **100** shown in FIG. **7**F). In summary, a waveguide having a blackening section disposed over at least one surface and a method of forming the blackening section over the over at least one surface of the waveguide are described herein. The blackening section is disposed on the surface of the substrate reduce the amount of stray light transmitted through the edge or peripheral of the surface and the amount of stray light scattered in the waveguide by the edge or peripheral of the first surface. The blackening material also functions to bond the cover substrate such that an air-gap is formed between cover substrate and the waveguide.

[0048] 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 device, comprising:

a substrate having a first surface, a second surface, and an edge, wherein the first surface of the substrate comprises a waveguide, wherein the waveguide includes an input coupling grating, a pupil expansion grating, and an output coupling grating;

a cover substrate;

a blackening section disposed over the first surface of the substrate between the edge of the substrate and the waveguide; and

a gap between the substrate and the cover substrate.

2. The device of claim **1**, further comprising an adhesive disposed over the blackening section.

3. The device of claim **2**, wherein the adhesive is a pressure sensitive adhesive.

4. The device of claim **2**, wherein the cover substrate is coupled to the adhesive.

5. The device of claim **1**, further comprising a blackening layer on at least the edge of the substrate.

6. The device of claim **5**, wherein the blackening section contacts the blackening layer.

7. The device of claim **1**, further comprising a gap setting feature wherein the blackening section is disposed on or around the gap setting feature.

8. The device of claim **1**, wherein the blackening section defines the gap between the substrate and the cover substrate.

9. The device of claim **1**, wherein the blackening section is disposed around a circumference of the first surface.

10. The device of claim **1**, wherein the blackening section comprises a blackening material, wherein the blackening material comprises a blacking ink, a siloxane-containing resin, or combinations thereof.

11. The device of claim **1** wherein, a blackening material and the substrate have a refractive index that is substantially similar.

12. The device of claim **11**, wherein the refractive index of the substrate is at least 1.4.

13. A method, comprising:

forming a blackening layer on at least an edge of a substrate, the substrate having a first surface and a second surface, the first surface comprising a waveguide comprising at least one grating disposed over the first surface of the substrate;

disposing a blackening material over the first surface, the blackening material disposed between the grating and the edge of the substrate;

placing a cover substrate on the blackening material; and

curing the blackening material to form a blackening section and bond the cover substrate to the blackening section.

14. The method of claim **13**, further comprising disposing gap setting features on at least the first surface of the substrate before forming the blackening layer.

15. The method of claim **14**, wherein the blackening material is disposed over the gap setting features.

16. The method of claim **15**, wherein the gap setting features and the blackening material are screen printed onto the substrate.

17. The method of claim **15**, wherein the gap setting features soak in the blackening material.

18. A method, comprising:

disposing a blackening material over a first surface of a substrate, the substrate having the first surface and a second surface, wherein the first surface comprises at least one waveguide, the blackening material disposed between a grating and an edge of the substrate;

curing the blackening material to form a blackening section;

disposing an adhesive over the blackening section;

curing the adhesive; and

placing a cover substrate on the adhesive.

19. The method of claim **18**, further comprising repeating the method on the second surface of the substrate.

20. The method of claim **18**, further comprising:
singulating the waveguide from the substrate, wherein the substrate comprises a plurality of waveguides; and
forming a blackening layer over at least the edge of the substrate comprising the waveguide.

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