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(54) **HIGH INDEX EDGE BLACKENING MATERIAL**

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See application file for complete search history.

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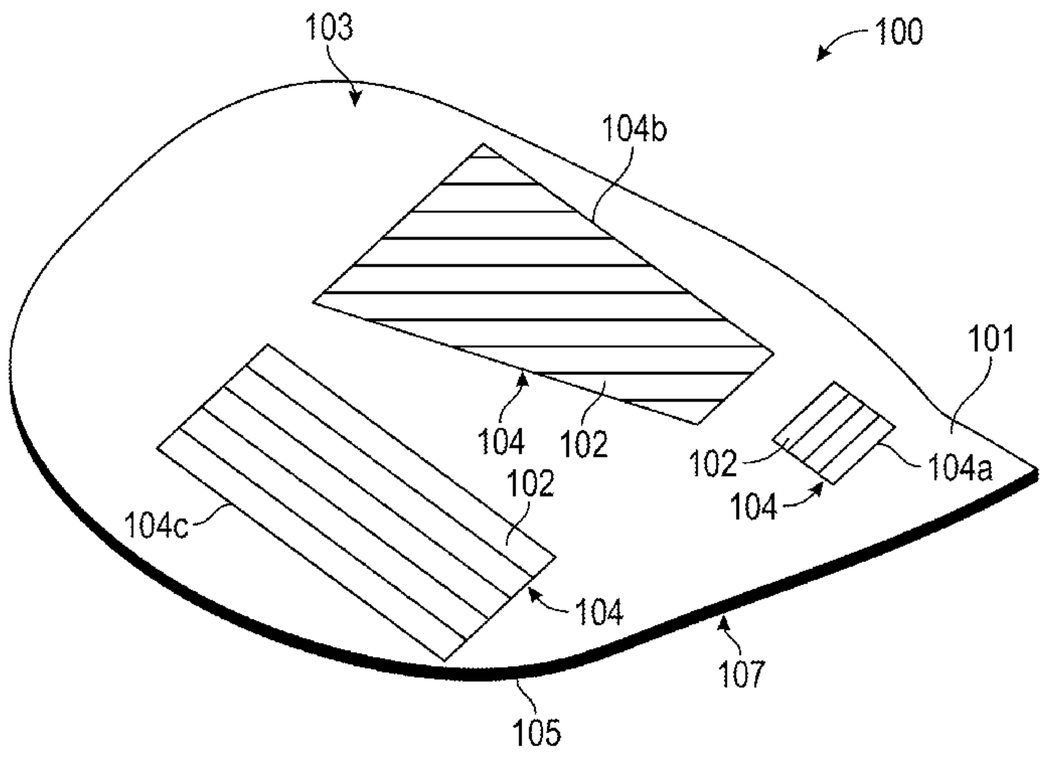
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(57) **ABSTRACT**

Embodiments described herein include a waveguide combiner having an edge coated with an optically absorbent composition and a method of coating the edge of the waveguide combiner with the optically absorbent composition. The optically absorbent composition includes one or more types of nanoparticles or microparticles, at least one of one or more dyes or one or more pigments, and a polymer matrix of one or more binders. The method includes producing an optically absorbent formulation. The optically absorbent formulation includes one or more types of particles, at least one of one or more dyes or one or more pigments, one or more binders, and one or more solvents. The optically absorbent formulation is applied on an edge of a waveguide combiner using an edge blackening tool. The formulation is cured with radiation to form the optically absorbent composition.

22 Claims, 1 Drawing Sheet



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G02B 27/01 (2006.01)

(52) **U.S. Cl.**
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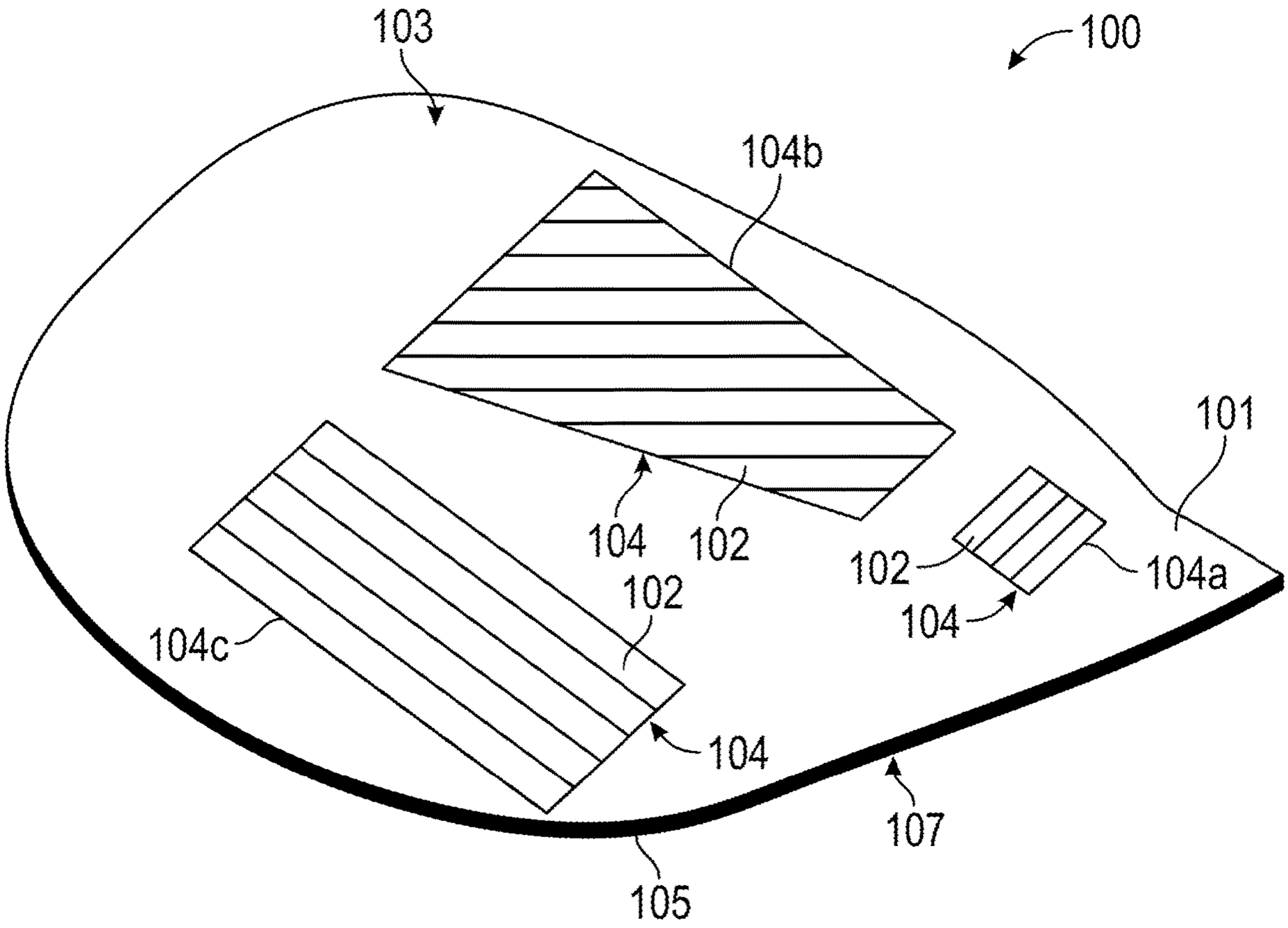

103
100
104b
101
104
102
102
104a
104
102
104c
104
107
105

FIG. 1

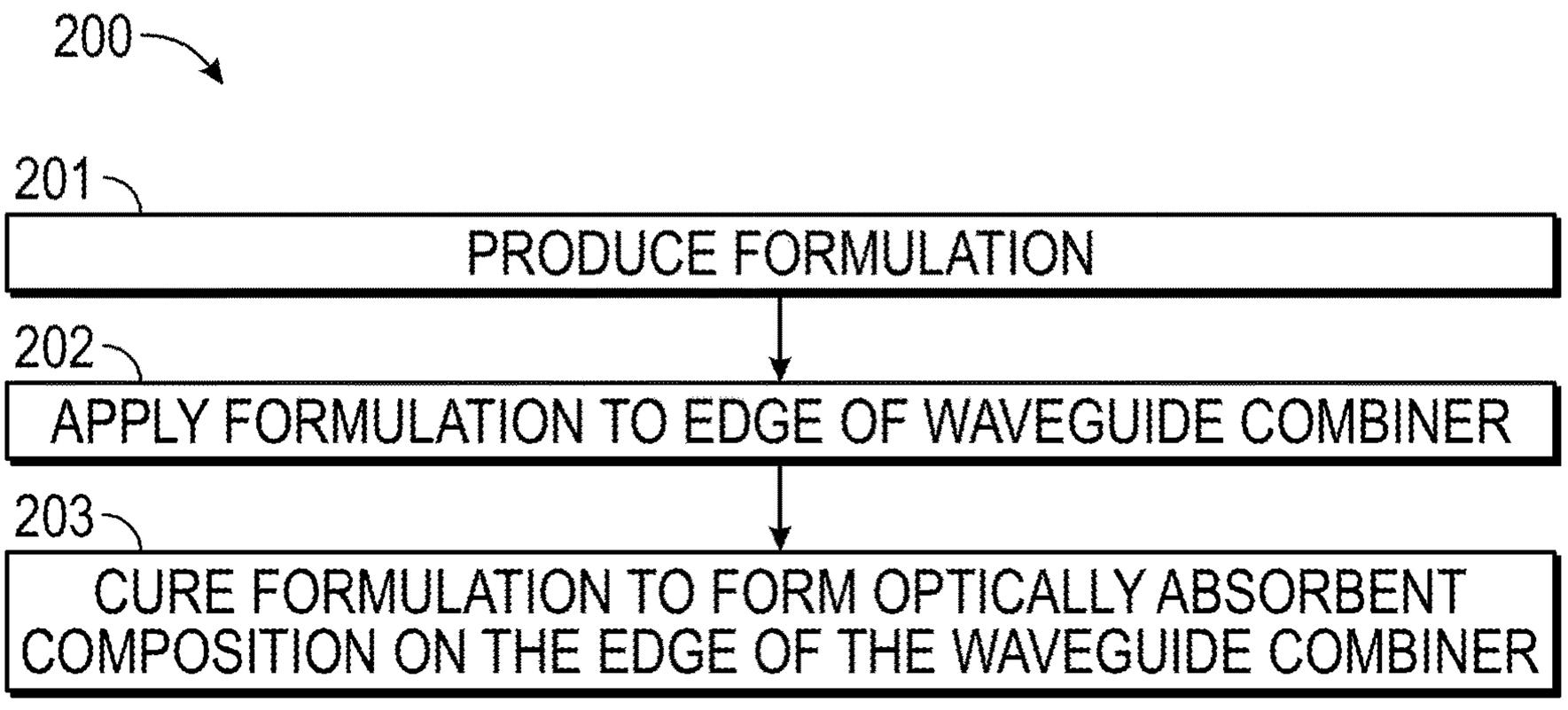

200
201
PRODUCE FORMULATION
202
APPLY FORMULATION TO EDGE OF WAVEGUIDE COMBINER
203
CURE FORMULATION TO FORM OPTICALLY ABSORBENT COMPOSITION ON THE EDGE OF THE WAVEGUIDE COMBINER

FIG. 2

HIGH INDEX EDGE BLACKENING MATERIAL

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to United States Provisional Patent Application Ser. No. 63/135,195, filed on Jan. 8, 2021, which is herein incorporated by reference.

BACKGROUND

Field

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate a waveguide combiner having an edge coated with an optically absorbent composition and a method of coating the edge of the waveguide combiner with the optically absorbent composition.

Description of the Related Art

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.

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.

One such challenge is displaying a virtual image overlaid on an ambient environment. Waveguide combiners, such as augmented reality waveguide combiners, are used to assist in overlaying images. Generated light is propagated through a waveguide combiner until the light exits the waveguide combiner and is overlaid on the ambient environment. Optical devices may require coating the edge of the waveguide combiner. The coating improves the performance of the waveguide combiner.

Accordingly, what is needed in the art is a waveguide combiner having an edge coated with an optically absorbent composition and a method of coating the edge of the waveguide combiner with the optically absorbent composition.

SUMMARY

In one embodiment, a waveguide combiner is provided. The waveguide combiner includes a substrate, a plurality of structures disposed on the substrate, an edge, and an optically absorbent composition disposed on the edge of the substrate. The optically absorbent composition includes one or more types of nanoparticles or microparticles, at least one of one or more dyes or one or more pigments, and a polymer matrix of one or more binders.

In another embodiment, a waveguide combiner is provided. The waveguide combiner includes a substrate having a substrate refractive index greater than about 1.8, a plurality of structures disposed on the substrate, an edge, and an optically absorbent composition disposed on the edge of the substrate. The optically absorbent composition has a refractive index of about 1.7 or greater and an optical density of about 2.0 or greater. The optically absorbent composition includes one or more types of nanoparticles or microparticles, at least one of one or more dyes or one or more pigments, and a polymer matrix of one or more binders. The one or more types of nanoparticles or microparticles are disposed in and supported by the polymer matrix, and the one or more binders are curable by radiation.

In yet another embodiment, a method is provided. The method includes producing an optically absorbent formulation. The optically absorbent formulation includes one or more types of particles, at least one of one or more dyes or one or more pigments, one or more binders, and one or more solvents. The optically absorbent formulation is applied on an edge of a waveguide combiner using an edge blackening tool. The formulation is cured with radiation to form an optically absorbent composition that includes the one or more types of particles, the at least one of one or more dyes or one or more pigments, and a polymer matrix of the one or more binders, wherein the particles are disposed in and supported by the polymer matrix.

BRIEF DESCRIPTION OF THE DRAWINGS

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.

FIG. **1** is a perspective, frontal view of a waveguide combiner according to embodiments.

FIG. **2** is a flow diagram of a method of forming an optically absorbent composition on an edge of a waveguide combiner.

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

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to a waveguide combiner having an edge coated with an optically absorbent composition and a method of coating the edge of the waveguide combiner with the optically absorbent composition.

The waveguide combiner includes a substrate, a plurality of structures disposed on the substrate, an edge, and an optically absorbent composition disposed on the edge of the substrate. The optically absorbent composition includes one or more types of nanoparticles or microparticles, at least one of one or more dyes or one or more pigments, and a polymer matrix of one or more binders. The method includes producing an optically absorbent formulation. The optically

absorbent formulation includes one or more types of particles, at least one of one or more dyes or one or more pigments, one or more binders, and one or more solvents. The optically absorbent formulation is applied on an edge of a waveguide combiner using an edge blackening tool. The formulation is cured with radiation to form an optically absorbent composition that includes the one or more types of particles, the at least one of one or more dyes or one or more pigments, and a polymer matrix of the one or more binders, wherein the particles are disposed in and supported by the polymer matrix.

FIG. **1** is a perspective, frontal view of a waveguide combiner **100** according to embodiments. It is to be understood that the waveguide combiner **100** described herein is an exemplary waveguide combiner and other waveguide combiners may benefit the advantages provided from this disclosure. The waveguide combiner **100** includes a plurality of structures **102** disposed on a surface **103** of a substrate **101**. The structures **102** may be nanostructures having sub-micron dimensions, e.g., nano-sized dimensions. The waveguide combiner **100** includes regions of the structures **102** corresponding to one or more gratings **104**, such as a first grating **104***a*, a second grating **104***b*, and a third grating **104***c*. The waveguide combiner **100** includes at least the first grating **104***a* corresponding to an input coupling grating and the third grating **104***c* corresponding to an output coupling grating. The waveguide combiner **100** may further include the second grating **104***b* corresponding to an intermediate grating.

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 optical device substrate **101** is configured such that the optical device substrate **101** transmits greater than or equal to about 50% to about 100%, of an infrared to ultraviolet region of the light spectrum. The optical device substrate **101** may be formed from any suitable material, provided that the optical device substrate **101** can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the waveguide combiner **100** described herein. Substrate selection may include optical device substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, and combinations thereof. In some embodiments, which may be combined with other embodiments described herein, the substrate **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, or combinations thereof. In another embodiment, which may be combined with other embodiments described herein, the substrate **101** has a refractive index greater than about 1.8. The substrate **101** having a refractive index greater than about 1.8 includes, but is not limited to, lithium tantalate ($LiTaO_3$), lithium niobate ($LiNbO_3$), SiC, or combinations thereof.

In operation of the waveguide combiner **100** a virtual image is projected from a near-eye display, such as a microdisplay, to the first grating **104***a*. The structures **102** 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 combiner **100** until the diffracted beams come in contact with structures **102** 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 combiner **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 **102** of the second grating **104***b*, and a third portion of beams that are coupled through the waveguide combiner **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 **102** until the either the intensity of the second portion of beams coupled through the waveguide combiner **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*.

The beams pass through the waveguide combiner **100** to the third grating **104***c* and undergo TIR in the waveguide combiner **100** until the beams contact a structure of the plurality of gratings **102** of the third grating **104***c* where the beams are split into beams that are refracted back or lost in the waveguide combiner **100**, beams that undergo TIR in the third grating **104***c* until the beams contact another structure of the plurality of gratings **102**, or beams that are out-coupled from the waveguide combiner **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 **102** until the either the intensity of the beams pass through the waveguide combiner **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.

Some light provided to the waveguide combiner **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 combiner **100**. Upon reaching the edge **105**, the stray light can then be (1) transmitted through the edge **105**, (2) reflected, or scattered, through the waveguide combiner **100** at a variety of angles, or (3) absorbed at the edge **105**. Stray light that is transmitted through the edge **105** and/or stray light that is scattered from the edge **105** through the waveguide combiner **100** reduce the quality of virial 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 combiner **100** by the edge **105**, the edge **105** is coated with an optically absorbent composition **107**.

The optically absorbent composition **107** includes one or more types of particles, at least one of one or more dyes or one or more pigments, and a polymer matrix of one or more binders. In some embodiment, the optically absorbent composition **107** further includes one or more filler dispersions, one or more photoiniators, one or more epoxy resins, one or more additives, one or more silanes, one or more isocyanates, one or more acids, one or more phosphine oxides, or combinations thereof. Examples of the filler dispersions include acrylates or methacrylates. Examples of the additives include amines or amides. Example of the dyes include organic dyes. The one or more pigments include, but are not limited to, carbon black, carbon nanotubes, iron oxide black, black pigments, or combinations thereof. The one or more

binders, as described herein in a method **200** of forming an optically absorbent composition **107** on an edge **105** of a waveguide combiner **100**, are operable to be cured by radiation, to form a polymer matrix. The one or more types of particles are disposed in the polymer matrix. The one or more binders include, but are not limited to, a UV curable binder, a LED curable binder, a thermal curable binder, an infrared curable binder, or combinations thereof.

The one or more types of particles include, but are not limited to, titanium oxide (TiO_2), Si, zirconium oxide (ZrO_2), zinc oxide (ZnO), ferrosoferric oxide (Fe_3O_4), germanium (Ge), SiC, diamond, dopants thereof, or any combination thereof. The one or more types of particles includes at least of nanoparticles or microparticles. Each nanoparticle (NP) or microparticle (MP) can be a coated particle, such as one, two, or more shells disposed around a core. In some examples, the NPs or MPs can contain one or more types of ligands coupled to the outer surface of the NPs or MPs (e.g., ligated NPs or stabilized NPs). The NPs or MPs can have one or more different shapes or geometries, such as spherical, oval, rod, cubical, wire, cylindrical, rectangular, or combinations thereof. The NPs can have a size or a diameter of about 2 nm, about 5 nm, about 8 nm, about 10 nm, about 12 nm, about 15 nm, about 20 nm, about 25 nm, about 30 nm, or about 35 nm to about 40 nm, about 50 nm, about 60 nm, about 80 nm, about 100 nm, about 150 nm, or about 200 nm. For example, the NPs can have a size or a diameter of about 2 nm to about 200 nm, about 2 nm to about 150 nm, about 2 nm to about 100 nm, about 2 nm to about 80 nm, about 2 nm to about 60 nm, about 2 nm to about 50 nm, about 2 nm to about 40 nm, about 2 nm to about 30 nm, about 2 nm to about 20 nm, about 2 nm to about 15 nm, about 2 nm to about 10 nm, about 10 nm to about 200 nm, about 10 nm to about 150 nm, about 10 nm to about 100 nm, about 10 nm to about 80 nm, about 10 nm to about 60 nm, about 10 nm to about 50 nm, about 10 nm to about 40 nm, about 10 nm to about 30 nm, about 10 nm to about 20 nm, about 10 nm to about 15 nm, about 50 nm to about 200 nm, about 50 nm to about 150 nm, about 50 nm to about 100 nm, about 50 nm to about 80 nm, or about 50 nm to about 60 nm.

A particle refractive index of the one or more types of particles is greater than 2.0. In some embodiments, which can be combined with other embodiments described herein, the particle refractive index of the one or more types of particles is about 2.4 or greater. The particle refractive index greater than 2.0 provide for the optically absorbent composition **107** having a refractive index of about 1.7 or greater. The optical density of the optically absorbent composition **107** of about 2.0 or greater is provide by the at least one of one or more dyes or one or more pigments. The refractive index of about 1.7 or greater and the optical density of about 2.0 or greater reduce the amount of stray light transmitted through the edge **105** and the amount of stray light scattered in the waveguide combiner **100** by the edge **105**. The refractive index of about 1.7 or greater of the optically absorbent composition **107** is matched to high refractive index substrates, i.e., the substrate **101** having a refractive index greater than about 1.8, to provide for further absorption of stray light. The optically absorbent composition **107** formed by the method **200** described herein utilizes an formulation that provides for a viscosity, surface tension, chemical and physical stability, and environmental reliability such that the formulation is operable to be applied to the edge **105** with an edge blacking tool and remain on the edge **105** prior to curing.

FIG. **2** is a flow diagram of a method **200** of forming an optically absorbent composition **107** on an edge **105** of a waveguide combiner **100**. To facilitate explanation, the method **200** will be described with reference to the waveguide combiner **100** of FIG. **1**. However, it is to be noted that the waveguide combiner **100** is an exemplary waveguide combiner and other waveguide combiners may have an edge coated with the optically absorbent composition **107** in conjunction with method **200**.

At operation **201**, a formulation is produced. The formulation includes one or more types of particles, at least one of one or more dyes or one or more pigments, one or more binders, and one or more solvents. The formulation may further include one or more filler dispersions, one or more photoiniators, one or more epoxy resins, 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 one or more solvents are operable to evaporate or vaporize upon application on the formulation to the edge **105** of the waveguide combiner **100**. The formulation provides for a viscosity, surface tension, chemical and physical stability, and environmental reliability such that the formulation is operable to be applied to the edge **105** with an edge blacking tool and remain on the edge **105** prior to curing. The formulation has a viscosity of about 1 kcP to 100 kcP. At operation **202**, the formulation is applied to the edge **105** of the waveguide combiner **100**. The formulation may be applied with an edge blackening tool. In one example, the edge blackening tool includes a substrate support operable to retain an optical device substrate, a first actuator configured to rotate the substrate support; a holder configured to hold a coating applicator against the edge **105** of the substrate **100** when the substrate **100** is rotated on the substrate support, a second actuator operable to apply a force on the holder in a direction towards the substrate support to apply the formulation to the edge **105**.

The one or more solvents evaporate or vaporize and the one or more types of particles, at least one of one or more dyes or one or more pigments, one or more binders remain. At operation **203**, the formulation is cured to form the optically absorbent composition **107** on the edge **105** of the waveguide combiner **100**. The one or more binders are cured by radiation to form a polymer matrix. The one or more types of particles are disposed in and supported by the polymer matrix. The one or more binders include, but are not limited to, a UV curable binder, a LED curable binder, a thermal curable binder, an infrared curable binder, or combinations thereof. Thus, the cure process of operation **203** includes a UV cure process, a LED cure process, a thermal cure process, an infrared cure process, or a combination thereof.

In summation, a waveguide combiner having an edge coated with an optically absorbent composition and a method of coating the edge of the waveguide combiner with the optically absorbent composition are described herein. The optically absorbent composition formed the method described herein utilizes an formulation that provides for a viscosity, surface tension, chemical and physical stability, and environmental reliability such that the formulation is operable to be applied to the edge with an edge blacking tool and remain on the edge prior to curing. The one or more binders are cured by radiation to form a polymer matrix. The one or more types of particles are disposed in and supported by the polymer matrix. The refractive index of about 1.7 or greater and the optical density of about 2.0 or greater of the optically absorbent composition reduce the amount of stray light transmitted through the edge and the amount of stray light scattered in the waveguide combiner by the edge.

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.

What is claimed is:

1. A waveguide combiner, comprising:
a substrate having an outer edge;
a plurality of structures disposed on the substrate; and
an optically absorbent composition disposed on the outer edge of the substrate, the optically absorbent composition comprising:
one or more types of particles;
at least one of one or more dyes or one or more pigments;
a polymer matrix of one or more binders; and
a refractive index of 1.7 or greater.

2. The waveguide combiner of claim **1**, wherein regions of the optical device structures correspond to one or more gratings.

3. The waveguide combiner of claim **2**, wherein the one or more gratings include an input coupling grating and an output coupling grating.

4. The waveguide combiner of claim **1**, wherein the one or more types of particles comprise at least nanoparticles or microparticles.

5. The waveguide combiner of claim **4**, wherein the nanoparticles or microparticles contain one or more types of ligands coupled to an outer surface of the nanoparticles or microparticles.

6. The waveguide combiner of claim **1**, wherein a particle refractive index of the one or more types of particles is greater than 2.0.

7. The waveguide combiner of claim **1**, wherein the one or more types of particles comprise titanium oxide (TiO_2), silicon (Si), zirconium oxide (ZrO_2), zinc oxide (ZnO), ferrosoferric oxide (Fe_3O_4), germanium (Ge), silicon carbide (SiC), diamond, dopants thereof, or any combination thereof.

8. The waveguide combiner of claim **1**, wherein the optically absorbent composition further comprises one or more filler dispersions, one or more photoinitiators, one or more epoxy resins, one or more additives, one or more silanes, one or more isocyanates, one or more acids, one or more phosphine oxides, or combinations thereof.

9. The waveguide combiner of claim **1**, wherein the optically absorbent composition has an optical density of about 2.0 or greater.

10. The waveguide combiner of claim **1**, wherein the one or more pigments comprise carbon black, carbon nanotubes, iron oxide black, black pigments, or combinations thereof.

11. The waveguide combiner of claim **1**, wherein the one or more binders comprise a UV curable binder, a LED curable binder, a thermal curable binder, an infrared curable binder, or combinations thereof.

12. The waveguide combiner of claim **1**, wherein the substrate comprises 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.

13. The waveguide combiner of claim **1**, wherein the one or more types of particles are disposed in and supported by the polymer matrix.

14. A waveguide combiner, comprising:
a substrate having an outer edge and a substrate refractive index greater than about 1.8, the substrate comprising silicon carbide (SiC), lithium niobate ($LiNbO3$), lithium tantalate ($LiTaO3$), or combinations thereof;
a plurality of structures disposed on the substrate; and
an optically absorbent composition disposed on the outer edge of the substrate, the optically absorbent composition having a refractive index of about 1.7 or greater and an optical density of about 2.0 or greater, the optically absorbent composition comprising:
one or more types of nanoparticles or microparticles;
at least one of one or more dyes or one or more pigments; and
a polymer matrix of one or more binders, wherein:
the one or more types of nanoparticles or microparticles are disposed in and supported by the polymer matrix; and
the one or more binders are curable by radiation.

15. The waveguide combiner of claim **14**, wherein the one or more binders comprise a UV curable binder, a LED curable binder, a thermal curable binder, an infrared curable binder, or combinations thereof.

16. The waveguide combiner of claim **14**, wherein the plurality of structures are nanostructures having sub-micron dimensions.

17. A method, comprising:
producing an optically absorbent formulation, the optically absorbent formulation comprising:
one or more types of particles;
at least one of one or more dyes or one or more pigments;
one or more binders; and
one or more solvents;
applying the optically absorbent formulation on an outer edge of a waveguide combiner using an edge blackening tool; and
curing the formulation with radiation to form an optically absorbent composition comprising:
the one or more types of particles;
the at least one of one or more dyes or one or more pigments;
a polymer matrix of the one or more binders, wherein the particles are disposed in and supported by the polymer matrix; and
a refractive index of 1.7 or greater.

18. The method of claim **17**, wherein the one or more binders comprise a UV curable binder, a LED curable binder, a thermal curable binder, an infrared curable binder, or combinations thereof.

19. The method of claim **18**, wherein curing the formulation comprises a UV cure process, a LED cure process, a thermal cure process, an infrared cure process, or a combination thereof.

20. The method of claim **17**, wherein the optically absorbent composition has an optical density of about 2.0 or greater.

21. The method of claim **17**, wherein the substrate comprises silicon carbide (SiC), lithium niobate ($LiNbO_3$), or combinations thereof.

22. The waveguide combiner of claim **4**, wherein the one or more types of particles are coated particles having a shell disposed around a core.

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