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(54) **FORMING OPTICAL DEVICE USING MIXED-PARTICLE LAYER**

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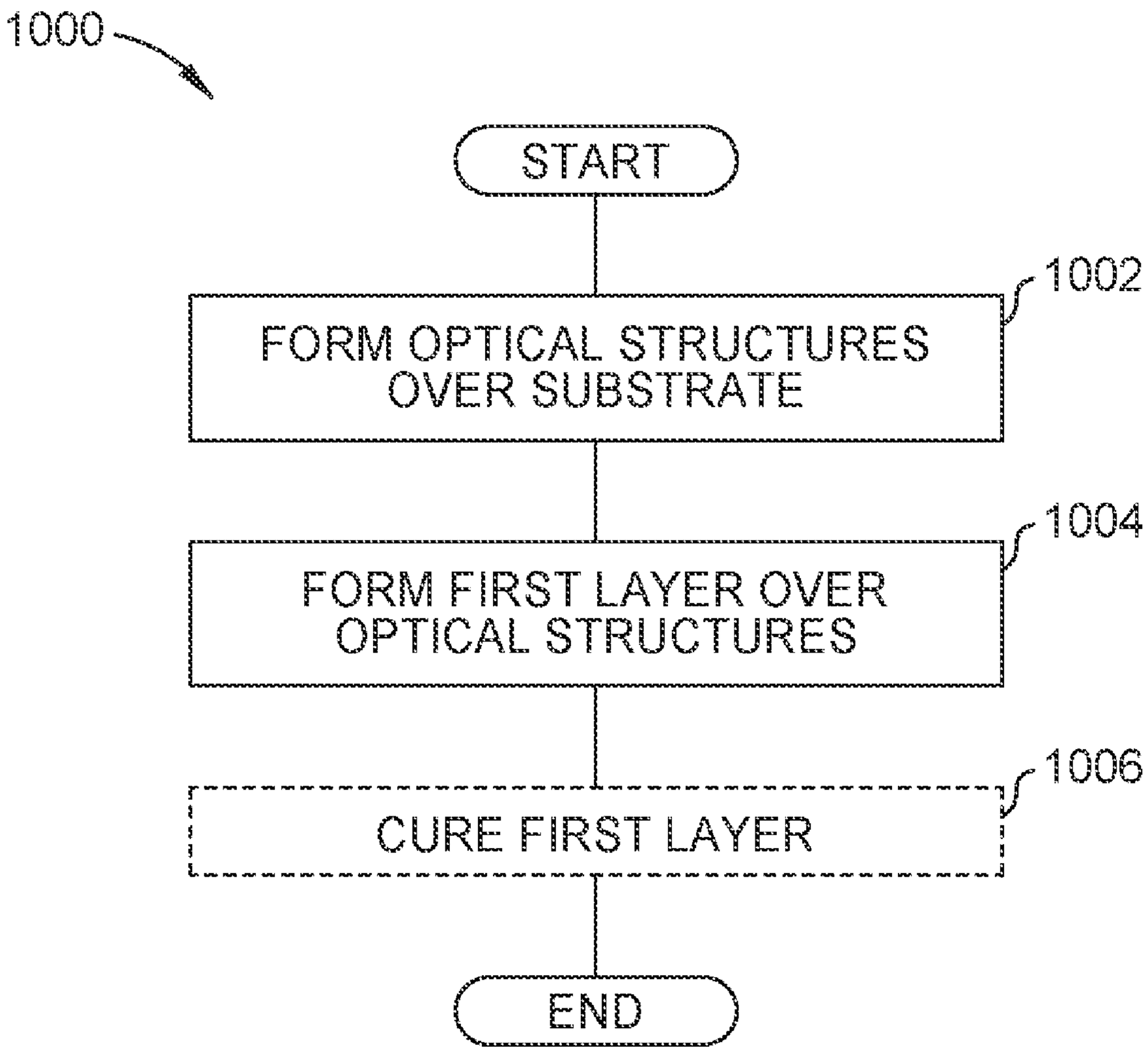
(57) **ABSTRACT**

A method of forming an optical device is provided. The method includes forming a first layer over a plurality of optical structures, the first layer including a first plurality of nanoparticles and a second plurality of nanoparticles. The first plurality of nanoparticles and the second plurality of nanoparticles are formed of a first material, the first plurality of nanoparticles have a first average volume, greater than 95% of the first plurality of nanoparticles have a volume within 10% of the first average volume, the second plurality of nanoparticles have a second average volume, greater than 95% of the second plurality of nanoparticles have a volume within 10% of the second average volume, and the second average volume is at least 25% larger the first average volume.



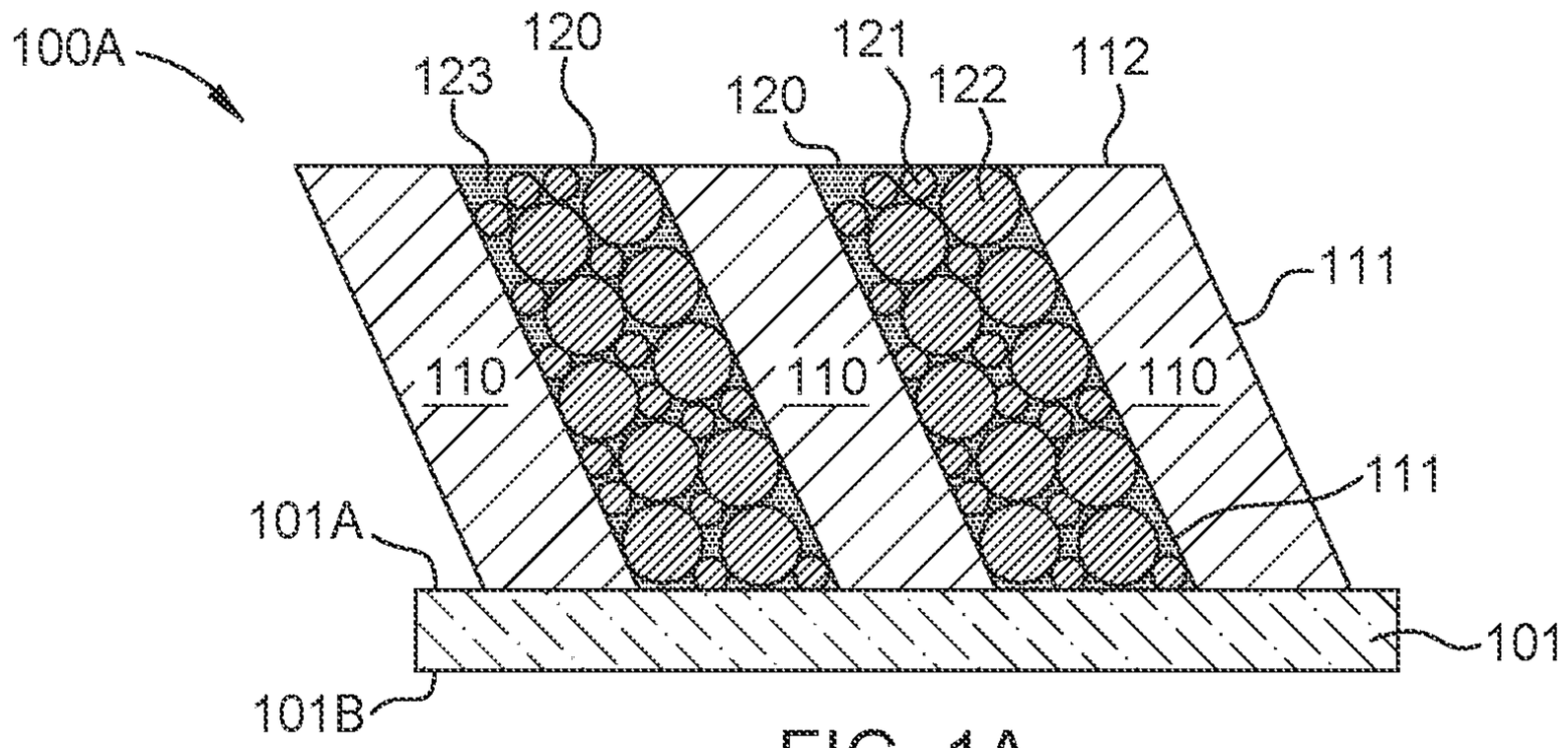


FIG. 1A

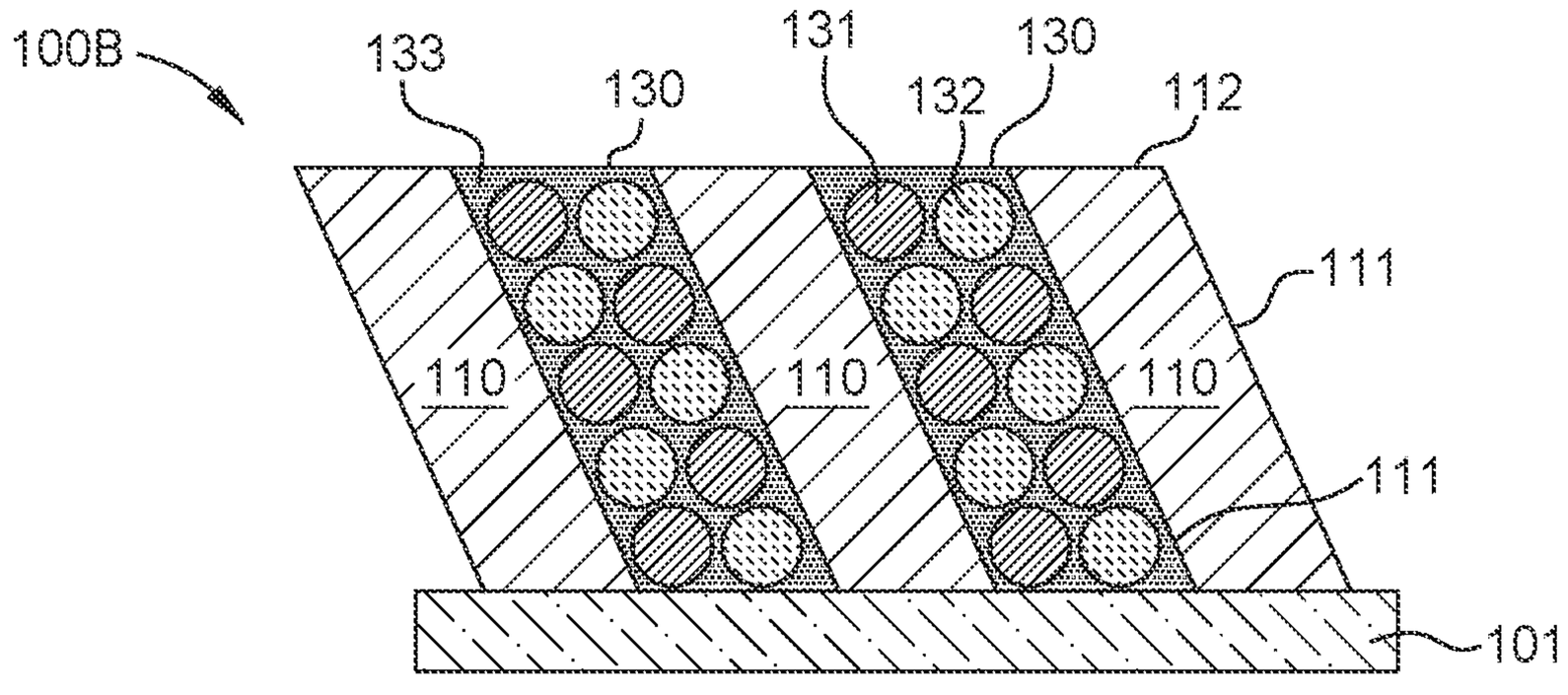


FIG. 1B

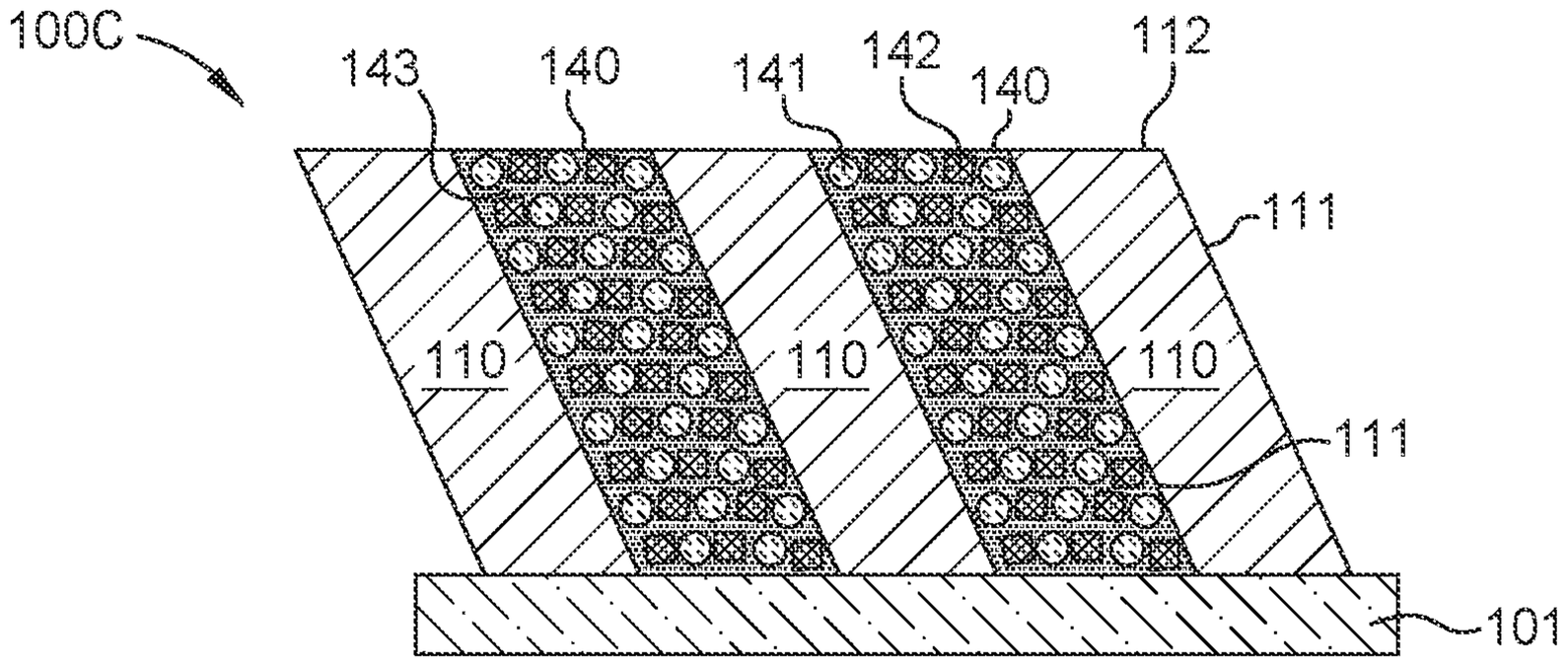


FIG. 1C

1000
START
FORM OPTICAL STRUCTURES OVER SUBSTRATE
1002
FORM FIRST LAYER OVER OPTICAL STRUCTURES
1004
CURE FIRST LAYER
1006
END

FIG. 2

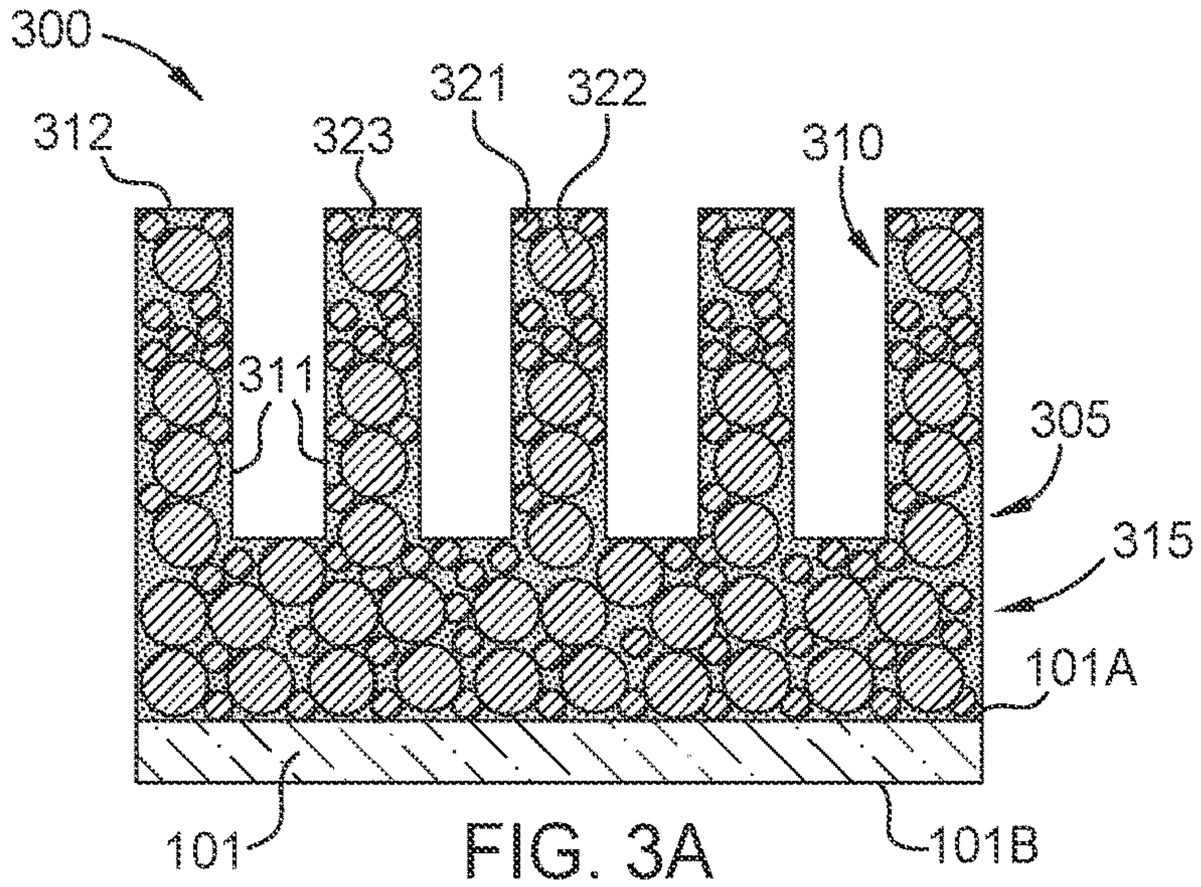


FIG. 3A

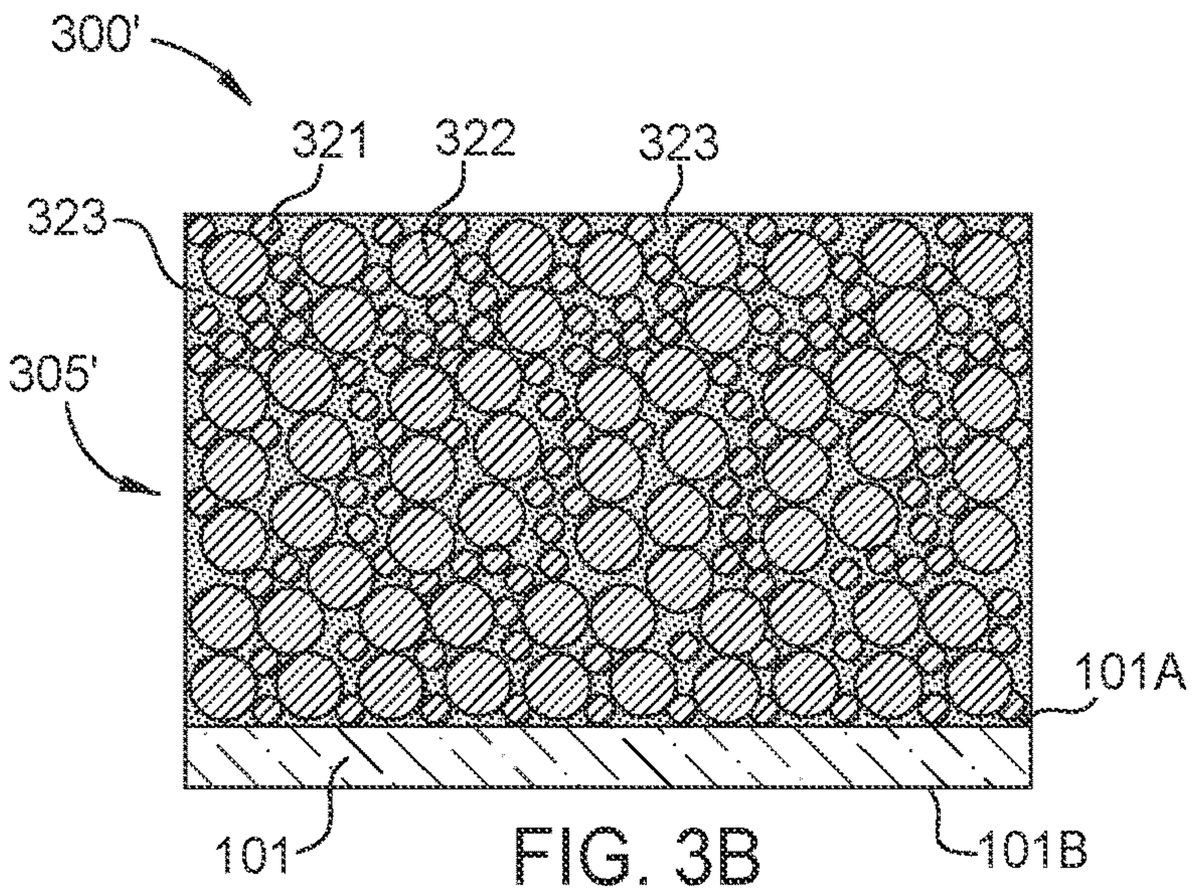


FIG. 3B

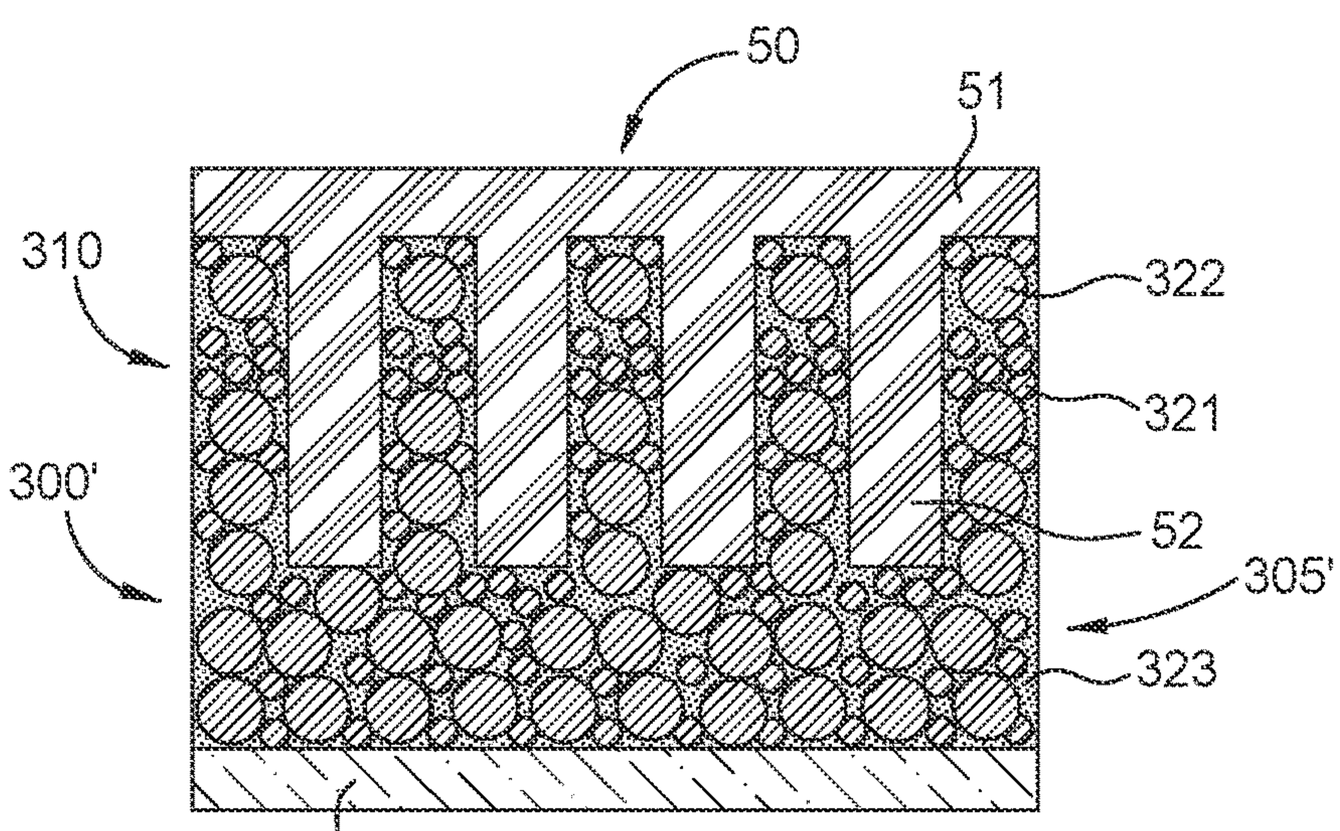


FIG. 3C

FORMING OPTICAL DEVICE USING MIXED-PARTICLE LAYER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/358,011, filed on Jul. 1, 2022. The contents of this provisional patent application is herein incorporated by reference.

BACKGROUND

[0002] Embodiments of the present disclosure generally relate to optical devices including a mixed-particle layer and methods for forming optical devices using a mixed-particle layer.

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 to appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

[0005] One such challenge is displaying a virtual image overlaid on an ambient environment. Optical devices including waveguide combiners, such as augmented reality waveguide combiners, and flat optical devices, such as metasurfaces, are used to assist in overlaying images. Generated light is propagated through an optical device until the light exits the optical device and is overlaid on the ambient environment. Optical loss during propagation of the light inside the optical device remains a problem. Furthermore, it can often be beneficial for optical performance to use materials having a high refractive index (e.g., a refractive index>2.0), but an increase of the refractive index often comes with an increase in optical loss.

[0006] Accordingly, what is needed in the art are optical devices that can deliver the intended optical performance with high-refractive index materials without significant amounts of optical loss and methods for forming these optical devices.

SUMMARY

[0007] In one embodiment, a method of forming an optical device is provided. The method includes forming a first layer over a plurality of optical structures, the first layer including a first plurality of nanoparticles and a second plurality of nanoparticles, wherein the first plurality of nanoparticles have a first average volume, greater than 95% of the first plurality of nanoparticles have a volume within 10% of the first average volume, the second plurality of nanoparticles have a second average volume, greater than 95% of the second plurality of nanoparticles have a volume within 10% of the second average volume, and the second average volume is at least 25% larger the first average volume.

[0008] In another embodiment, a method of forming an optical device is provided. The method includes forming a first layer over a plurality of optical structures, the first layer including a first plurality of nanoparticles and a second plurality of nanoparticles, wherein the first plurality of nanoparticles are formed of a first material and the second plurality of nanoparticles are formed of a second material, and the first plurality of nanoparticles and the second plurality of nanoparticles comprise greater than 95% of optically transparent nanoparticles in the first layer.

[0009] In another embodiment, a method of forming an optical device is provided. The method includes forming a first layer over a plurality of optical structures, the first layer including a first plurality of nanoparticles and a second plurality of nanoparticles, the first plurality of nanoparticles have a different geometry than the second plurality of nanoparticles, and the first plurality of nanoparticles and the second plurality of nanoparticles comprise greater than 95% of optically transparent nanoparticles in the first layer.

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] FIG. **1**A is a schematic, cross-sectional view of an optical device, according to one embodiment.

[0012] FIG. **1**B is a schematic, cross-sectional view of an optical device, according to one embodiment.

[0013] FIG. **1**C is a schematic, cross-sectional view of an optical device, according to one embodiment.

[0014] FIG. **2** is a process flow diagram of a method of forming the optical devices shown in FIGS. **1**A-**1**C, according to one embodiment.

[0015] FIG. **3**A is a schematic, cross-sectional view of an optical device, according to one embodiment.

[0016] FIG. **3**B is a schematic, cross-sectional view of an intermediate device, according to one embodiment.

[0017] FIG. **3**C is a schematic, cross-sectional view of an imprinting process being performed on the intermediate device of FIG. **3**B, according to one embodiment.

[0018] 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

[0019] Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to optical devices with high levels of optical performance and reduced levels of optical loss compared to conventional optical devices as wells as meth-

ods for forming these optical devices. The high levels of optical performance coupled with the low levels of optical loss are obtained by using one or more mixed-particle layers, such as layers having two or more different types of nanoparticles, as described in fuller detail below. Some exemplary different types of nanoparticles used in the mixed-particle layers can include particles of different sizes (see FIG. **1**A), particles of different materials (see FIG. **1**B), and particles of different geometries (see FIG. **1**C).

[0020] FIG. **1**A is a schematic, cross-sectional view of an optical device **100**A, according to one embodiment. The optical device **100**A includes nanoparticles of different sizes to improve the optical performance. Unless specifically noted otherwise, the following description of the optical device **100**A is also applicable to the optical device **100**B (FIG. **1**B) and the optical device **100**C (FIG. **1**C). In one embodiment, which can be combined with other embodiments described herein, the optical device **100**A is a waveguide combiner, such as an augmented reality waveguide combiner. In another embodiment, which can be combined with other embodiments described herein, the optical device **100**A is a flat optical device, such as a metasurface. Other optical devices that can be formed from the optical device **100**A include optical filters and dielectric mirrors.

[0021] The optical device **100**A includes an optical device substrate **101**, a plurality of optical device structures **110**, and an optical coating **120** (also referred to as first layer) disposed over the optical device structures **110** and the substrate **101**. The optical coating **120** includes particles **121**, **122** of different sizes as described in fuller detail below. In some embodiments, the optical coating **120** can contact the optical device structures. Used herein, with respect to coatings and layers, "over" refers to a coating or layer that is adjacent to another component without any relation to the relative vertical positioning of the coating and the other component. The optical coating **120** can include particles (e.g., optical nanoparticles) that can help improve the optical performance of the optical device **100**A.

[0022] In one embodiment, the optical device structures **110** are gratings of a waveguide combiner. The optical device substrate **101** includes a first surface **101**A and an opposing second surface **101**B. The optical device structures **110** are disposed over the first surface **101**A of the optical device substrate **101**. In some embodiments, the optical device structures **110** are disposed directly on the first surface **101**A of the substrate **101**.

[0023] The substrate **101** can be formed of any suitable material, provided that the substrate **101** can adequately transmit light of a specified wavelength or wavelength range and can serve as an adequate support for one or more optical devices formed on the substrate **101**.

[0024] In some embodiments, the substrate **101** can be formed of materials including, but not limited to, silicon carbide, amorphous dielectrics, crystalline dielectrics, silicon, silicon oxide, silicon carbide, silica (e.g., fused silica), sapphire, glass, magnesium oxide, diamond, lanthanum oxide, titanium oxide (e.g., TiO_2), tantalum oxide one or more polymers, oxide materials, nitride materials, sulfide materials, phosphide materials, telluride materials, or combinations thereof. In some embodiments, which can be combined with other embodiments described herein, the substrate **101** includes an optically transparent material. Furthermore, in some embodiments, a layer (not shown) can be disposed on the substrate **101**. The layer can be formed of a material that is more suitable for forming a pattern than the material of the substrate **101**. The layer can be formed from a variety of materials, such as silicon nitride (SiN), titanium oxide (TiO_2), silicon oxide (SiO_2), niobium oxide (Nb_2O_5), chromium, amorphous silicon or more than one material (e.g., TiO_2/SiO_2). In some embodiments, this layer can be used to form the optical device structures **110** or another feature on the optical device.

[0025] Each optical device structure **110** can include a top surface **112** and a pair of sidewalls **111**. In some embodiments, the plurality of optical device structures **110** can be spaced apart from each other in a direction parallel to the first surface **101**A of the substrate **101**. The optical device structures **110** include sub-micron critical dimensions, e.g., nanosized dimensions, corresponding to the widths of the optical device structures **110** that extend in the same direction in which the optical device structures **110** are spaced apart. In some embodiments, the optical device structures **110** may be binary structures (not shown) with sidewalls **111** perpendicular to the first surface **101**A of the substrate **101**. In other embodiments, the optical device structures **110** may be angled structures, for example as shown in FIG. **1**A, with at least one of the sidewalls **111** angled relative to the first surface **101**A of the substrate **101**.

[0026] The optical device structures **110** can be formed of an optically transparent material, such as any of the materials described below for the particles **121**, **122**. In one embodiment, the optical device structures **110** can be formed of a metal oxide (e.g., titanium oxide). In another embodiment, the optical device structures **110** can be formed of a stack of different layers, such as a stack of metal oxides (e.g., silicon oxide and titanium oxide).

[0027] The optical coating **120** is disposed over the optical device structures **110**. In some embodiments, the optical coating **120** can fill the entire gap between neighboring optical device structures **110**, for example as shown in FIG. **1**A. In other embodiments, a gap can remain after the optical coating **120** is applied over portions of the sidewalls **111** of the optical device structures **110**. Furthermore, in some embodiments the optical coating can be applied over the top surface **112** of the optical device structures **110** as well as in the gap between the optical device structures **110**.

[0028] The optical coating **120** includes a first plurality of particles **121**, a second plurality of particles **122**, and a binder **123**. The particles **121**, **122** can be substantially uniformly dispersed throughout the binder **123**. The particles **121**, **122** can be referred to as nanoparticles. In some embodiments, the particles **121**, **122** can have dimensions, such as a diameter for a roughly spherical nanoparticle from about 0.1 nm to about 1000 nm, such as from about 0.5 nm to about 500 nm, such as from about 1 nm to about 50 nm.

[0029] The binder **123** can include a curing agent that is configured to be cured thermally, from radiation (e.g., an ultraviolet cure), and/or from a chemical process. In some embodiments, the binder **123** can be formed of an organic binder. Some examples of materials that can be used for the binder **123** include an epoxy, thiol, silicone, acrylate, or methacrylate-based binder.

[0030] The first plurality of particles **121** and the second plurality of particles **122** can be formed of a variety of materials. In some embodiments, the particles **121**, **122** can be formed of a metal oxide, such as silicon oxide (SiO_2), titanium oxide (TiO_2), zirconium oxide (ZrO_2), niobium oxide (Nb_2O_5), hafnium oxide (HfO_2), vanadium oxide

(V_2O_5), lead oxide (PbO_2), tantalum oxide (Ta_2O_5), zinc oxide (ZnO), tin oxide (SnO_2), aluminum oxide (Al_2O_3), silver oxide (AgO, Ag_2O), or lithium oxide (Li_2O). In other embodiments, the particles **121**, **122** can be formed of a metal sulfide, such as cadmium sulfide (CdS), zinc sulfide (ZnS), tungsten (WS_2), copper sulfide (CuS), bismuth sulfide (Bi_2S_3), or antimony sulfide (Sb_2S_3). In other embodiments, the particles **121**, **122** can be formed of a metal selenide, such as cadmium selenide (CdSe) or mercury selenide (HgSe) or a metal telluride, such as cadmium telluride (CdTe). In other embodiments, the particles **121**, **122** can be formed of a nitride, such as gallium nitride (GaN) or a phosphide, such as indium phosphide (InP) or gallium phosphide (GaP). In other embodiments, the particles **121**, **122** can be formed of an element, such as silver, gold, copper, or silicon. In still other embodiments, the particles **121**, **122** can be formed of a perovskite material. In some embodiments, the particles **121**, **122** can have a structure that includes multiple materials. For example, in one embodiment, the particles **121**, **122** can have a structure with a shell of one material (e.g., SiO_2 or ZnS) surrounding a core of another material (e.g., TiO_2 or InP).

[0031] Additionally, in some embodiments the particles **121**, **122** can include one or more organic ligands (e.g., a fatty acid or polyester ligand) to increase solubility of the particles **121**, **122** in the binder **123** and allow for the particles **121**, **122** to be more uniformly dispersed throughout the binder **123**. Some additional examples of ligands can include ligand can be or include one or more carboxylic acids, one or more esters, one or more amines, one or more alcohols, one or more silanes, salts thereof, complexes thereof, or any combination thereof, oleic acid, stearic acid, propionic acid, benzoic acid, palmitic acid, myristic acid, methylamine, oleylamine, butylamine, benzyl alcohol, oleyl alcohol, butanol, octanol, dodecanol, octyltrimethoxy silane, octyltriethoxy silane, octenyltrimethoxy silane, octenyltri ethoxy silane, 3-trimethoxysilyl) propyl methacrylate, pro pyltriethoxy silane, salts thereof, esters thereof, complexes thereof, or any combination thereof. The ligands as well as the mixture of different sized particles can effect the viscosity of the coating **120** during application of the coating **120**. For example, a greater amount of smaller particles can lead to higher ligand loading, which can increase the viscosity.

[0032] In some embodiments, the particles **121**, **122** can be formed of the same material. In other embodiments, the particles **121**, **122** can be formed of different materials, for example as described below in reference to FIG. **1**B. Additionally, in some embodiments, the particles **121**, **122** can also have different geometries (e.g., a different crystal phase) but have a same composition (e.g., titanium oxide), for example as described below in reference to FIG. **1**C. Furthermore, although only two particles **121**, **122** are shown in FIG. **1**A, other embodiments can include three or more different particles. Additionally, each of the particles can have different sizes, be formed of different materials, and/or have different geometries relative to the other particles in the optical coating **120**.

[0033] Each particle in the second plurality of particles **122** can be substantially larger than each particle in the first plurality of particles **121**. For example, the average volume for a particle in the second plurality of particles **122** is at least 10% larger, 25% larger, 50% larger, two times larger, five times larger, or ten times larger than the average volume for a particle in the first plurality of particles **121**. Larger particles can generally have a higher refractive index, but can also cause more optical loss due to light scattering, which reduces optical performance. On the other hand, smaller particles cause less optical loss due to light scattering, but the refractive index is often lower.

[0034] In some embodiments, the first plurality of particles **121** and the second plurality of particles **122** can comprise greater than 95%, such as greater than 99% of all of the optically transparent nanoparticles of the material(s) in the optical coating **120** that form the first plurality of particles **121** and the second plurality of particles **122**.

[0035] Each of the first plurality of particles **121** and the second plurality of particles **122** accounts for a significant portion of the total amount of the particles **121**, **122**. For example, in many embodiments each of the plurality of particles **121**, **122** accounts for at least 5%, at least 10% or at least 25% of the total amount of particles **121**, **122**. In some embodiments, greater than 95%, such as greater than 99% of the particles in the first plurality of particles **121** have a volume that is within 10%, 5%, or 1% of the average volume for the first plurality of particles **121**. Similarly, in some embodiments, greater than 95%, such as greater than 99% of the particles in the second plurality of particles **122** have a volume that is within 10%, 5%, or 1% of the average volume for the second plurality of particles **122**. Furthermore, in these embodiments, the first plurality of particles **121** and the second plurality of particles **122** can comprise greater than 95%, such as greater than 99% of all of the nanoparticles of the material in the optical coating **120** that forms the first plurality of particles **121** and the second plurality of particles **122**. Thus, in these embodiments the sizes of the particles **121**, **122** do not overlap with each other except for potentially very small percentages (e.g., <1%). Having these high percentages of the nanoparticles be confined to these relatively narrow size ranges can be used to increase the packing density of the nanoparticles in the optical coating **120** because the smaller particles can fit inside voids between larger particles that would otherwise only include binder if only larger particles were included.

[0036] Increasing the particle density of layers including these optical nanoparticles can help improve the optical performance of the optical device **100**A by having more of the light passing through the coating **120** interact with an optical nanoparticle or more nanoparticles, such as particles **121**, **122**, as opposed to interacting only with the binder **123** or with less nanoparticles. This increased interaction can be useful when light is outcoupled from an optical device, such as when light is outcoupled from a waveguide combiner for use in an augmented reality application.

[0037] FIG. **1**B is a schematic, cross-sectional view of an optical device **100**B, according to one embodiment. The optical device **100**B includes nanoparticles of different materials to improve optical performance. The optical device **100**B is the same as the optical device **100**A described above except that the optical device **100**B includes an optical coating **130** instead of the optical coating **120** that is included in the optical device **100**A. The optical coating **130** includes a first plurality of particles **131**, a second plurality of particles **132**, and a binder **133**. In some embodiments, the binder **133** is the same as the binder **123** described above.

[0038] Each of the first plurality of particles **131** and the second plurality of particles **132** accounts for a significant portion of the total amount of the particles **131**, **132**. For

example, in many embodiments each of the plurality of particles **131**, **132** accounts for at least 5%, at least 10% or at least 25% of the total amount of particles **131**, **132**. The first plurality of particles **131** and the second plurality of particles **132** can comprise greater than 95%, such as greater than 99% of all of the optically transparent nanoparticles of the materials in the optical coating **130** that form the first plurality of particles **131** and the second plurality of particles **132**.

[0039] The particles **131**, **132** can be formed from any of the materials described above for the particles **121**, **122**. The first plurality of particles **131** is formed of a different material than the second plurality of particles **132**. In some embodiments, the chemical elements (i.e., elements on the Periodic Table of Elements) are the same in both particles and only the chemical composition is different, such as a first particle **131** of TiO_2 and a second particle **132** of Ti_2O_3. In other embodiments, at least one of the particles **131**, **132** includes at least one chemical element not included in the other particle **131**, **132**, such as a first particle **131** of silver and a second particle **132** of silver oxide.

[0040] In other embodiments, no chemical elements are shared between the two particles **131**, **132**. Thus, in these embodiments the first particles **131** are formed of a first material consisting of one or more chemical elements, the second particles **132** are formed of a second material consisting of one or more chemical elements that are each different from the one or more chemical elements that form the first material. For example, in one embodiment the first plurality of particles **131** can be formed of titanium oxide and the second plurality of particles **132** can be formed of gallium nitride.

[0041] By including particles **131**, **132** having different compositions, the optical coating **130** can formed to have optical properties (e.g., refractive index and optical loss) that would not be possible from an optical coating only having particles formed from a single material. Furthermore, although only two types of particles **131**, **132** are shown, other embodiments can include three or more types of particles in which each type of particle is formed from a different material to enable the formation of optical coatings with a larger variety of optical properties.

[0042] FIG. **1**C is a schematic, cross-sectional view of an optical device **100**C, according to one embodiment. The optical device **100**C includes nanoparticles of different geometries to improve the optical performance. The optical device **100**C is the same as the optical device **100**A described above except that the optical device **1008** includes an optical coating **140** instead of the optical coating **120** that is included in the optical device **100**A. The optical coating **140** includes a first plurality of particles **141**, a second plurality of particles **142**, and a binder **143**. In some embodiments, the binder **143** is the same as the binder **123** described above.

[0043] Each of the first plurality of particles **141** and the second plurality of particles **142** accounts for a significant portion of the total amount of the particles **141**, **142**. For example, in many embodiments each of the plurality of particles **141**, **142** accounts for at least 5%, at least 10% or at least 25% of the total amount of particles **141**, **142**. Furthermore, the first plurality of particles **141** and the second plurality of particles **142** can comprise greater than 95%, such as greater than 99% of all of the nanoparticles of the materials in the optical coating **140** that form the first plurality of particles **141** and the second plurality of particles **142**.

[0044] The particles **141**, **142** can be formed from any of the materials described above for the particles **121**, **122**. The particles **141**, **142** can be formed from a same material (e.g., titanium oxide) or different materials. The first plurality of particles **141** has a different geometry than the second plurality of particles **142**. These different geometries can include (1) particles with structures having a different crystal phase, (2) one particle having a crystal structure compared to another particle having an amorphous structure, or (3) particles have different three-dimensional shapes. In one embodiment for particles with structures of a different crystal phase, the first plurality of particles **141** can be formed of titanium oxide having a rutile phase (first crystal phase) and the second plurality of particles **142** can be formed of titanium oxide having an anatase phase (second crystal phase). Some of the different three-dimensional shapes that the structures of the particles can have include, but are not limited to spherical, cubic, rod, pyramidal, hexagonal, tetragonal, rhombohedral, orthorhombic, monoclinic and triclinic. By including particles **141**, **142** having different geometries, the optical coating **140** can formed to have optical properties (e.g., refractive index and optical loss) that would not be possible from an optical coating only having particles formed from a single material in which all of the particles have the same geometry. Furthermore, although only two types of particles **141**, **142** are shown, other embodiments can include three or more types of particles in which each type of particle has a different geometry to enable the formation of optical coatings with a larger variety of optical properties. Using particles **141**, **142** of different geometries can improve the optical performance of an optical device, for example by increasing the packing density of the optical particles in the coating as well as by forming a coating with a refractive index and optical loss characteristics that would not be obtainable if only one type of particle were used.

[0045] FIG. **2** is a process flow diagram of a method **1000** of forming the optical devices **100**A, **100**B, and **100**C shown in FIGS. **1**A-**1**C, according to one embodiment.

[0046] The method **1000** begins at block **1002**. At block **1002**, the plurality of optical structures **310** are formed over the substrate **101**. In some embodiments, forming the optical device structures **110** can include a deposition (e.g., a physical vapor deposition or a chemical vapor deposition) followed by one or more etching and/or lithography processes to remove the material in between each of the neighboring optical device structures **110**. In other embodiments, the optical device structures **110** can be formed by an imprinting process in which a material is imprinted with a stamp, and then the imprinted material is cured to form optical device structures **110**. An example of an optical device formed from an imprinting process is described below in reference to FIGS. **3**A-**3**C.

[0047] At block **1004**, the optical coating (first layer) is formed over the optical structures **310**. The optical coating formed at block **1004** can include the optical coating **120** (FIG. **1**A), the optical coating **130** (FIG. **1**B), or the optical coating **140** (FIG. **1**C). Each of these optical coatings **12**, **130**, **140** can be formed using a variety of processes, such as a spin-coating process, an inkjet process, or a spray-coating process. Generally, a spin-coating or spray-coating process

results in the optical coating also being formed over the top surfaces **112** of the optical structures **310**. On the other hand, an inkjet process can be used when the optical coating is only provided in the gaps between the optical structures **310** without applying the optical coating on the top surfaces **112** of the optical structures **310**, for example as shown in FIG. **1**A.

[0048] For each of the coatings **120**, **130**, **140**, the corresponding particles **121**, **122** (FIG. **1**A), **131**, **132** (FIG. **1**B), and **141**, **142** (FIG. **1**C) can be deposited simultaneously from a mixture that includes each of the corresponding particles and the binder, such as binder **123**.

[0049] At block **1006**, the optical coating formed at block **1004** can optionally be cured. Curing the optical coating **120** can maintain the position of the particles **121**, **122** relative to the optical structures **310**. Curing the optical coating can also cause the optical coating to have a consistent effect on the optical performance of the optical device **100**A, **100**B, **100**C during the useful life of the optical device.

[0050] FIG. **3**A is a schematic, cross-sectional view of an optical device **300**, according to one embodiment. The optical device **300** includes an optical layer **305** formed over a first surface **101**A of the substrate **101**. The optical layer **305** includes optical structures **310** and a base **315**. The substrate **101** can be the same substrate described above in reference to FIGS. **1**A-**1**C. The optical device **300** is similar to the optical device **100**A described above except that the optical device **300** includes the optical structures **310** instead of the optical structures **310**, and the optical device does not include the optical coating **120**. The optical structures **310** can be formed using an imprinting process using a stamp **50** as described below in reference to FIG. **3**C.

[0051] Each of the optical structures **310** include sidewalls **311** and a top surface **312**. In one embodiment, the optical structures **310** can be gratings of a waveguide combiner. Although the optical structures **310** are illustrated as having a different external structure than the optical structures **310**, in some embodiments, the external structure of the optical structures **310** can be highly similar to the optical structures **310** described above. For example, in some embodiments the optical structures **310** can have the same or highly similar dimensions to the optical structures **310**, such as height, width, angle relative to the substrate **101**, and spacing between the individual optical structures **310**.

[0052] The optical structures **310** can have a different internal structure relative to the optical structures **110** described above and can be formed by a different process. On the other hand, the optical structures **310** can have an internal structure that is similar to the optical coatings **120**, **130**, **140** described above. For example, the optical structures **310** can include a first plurality of particles **321**, a second plurality of particles **322**, and a binder **323**. The first plurality of particles **321** and the second plurality of particles **322** can be uniformly distributed throughout the binder **323**. The binder **323** can be formed of the same material as the binder **123** described above. Furthermore, the particles **321**, **322** can include any pair of the particles described above for the plurality of particles **121**, **122** (FIG. **1**A), **131**, **132** (FIG. **1**B), or **141**, **142** (FIG. **1**C). Additionally, although only two particles **321**, **322** are shown three or more different types of particles may be included.

[0053] FIG. **3**B is a schematic, cross-sectional view of an intermediate device **300'**, according to one embodiment. The intermediate device **300'** includes an optical layer **305'**. The optical layer **305'** is the optical layer **305** before an imprinting process is performed on the optical layer **305'** to form the optical layer **305**. The optical layer **305'** can be formed over the first surface **101**A of the substrate **101** using a variety of processes, such as a spin-coating process, an inkjet process, or a spray-coating process.

[0054] FIG. **3**C is a schematic, cross-sectional view of an imprinting process being performed on the intermediate device **300'**, according to one embodiment. A stamp **50** is used to imprint a pattern on the optical layer **305'**. The stamp **50** includes a base **51** and a plurality of patterned features **52**. The plurality of patterned features **52** can be used to form the gaps between the plurality of optical structures **310** in the optical device **300**. The gaps between the plurality of patterned features **52** can be used to form the plurality of optical structures **310**.

[0055] After the optical layer **305'** is imprinted with the stamp **50**, the optical layer **305'** can be cured to form the optical device **300** that includes optical layer **305** shown in FIG. **3**A. In some embodiments, the optical layer **305'** can be cured after releasing the stamp **50** from the optical layer **305'**. In other embodiments, the optical layer **305'** can be cured while the stamp **50** remains on the optical layer **305'**. After the optical device **300** is formed, in some embodiments, one of the optical coatings **120**, **130**, **140** described above can be formed over the optical structures **310** in a similar manner as described above for forming the optical coatings **120**, **130**, **140** over the optical structures **110**.

[0056] 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 method of forming an optical device comprising:

forming a first layer over a plurality of optical structures, the first layer including a first plurality of nanoparticles and a second plurality of nanoparticles, wherein

the first plurality of nanoparticles have a first average volume,

greater than 95% of the first plurality of nanoparticles have a volume within 10% of the first average volume,

the second plurality of nanoparticles have a second average volume,

greater than 95% of the second plurality of nanoparticles have a volume within 10% of the second average volume, and

the second average volume is at least 25% larger the first average volume.

2. The method of claim **1**, wherein

the first plurality of nanoparticles and the second plurality of nanoparticles are formed of a first material, and

the first plurality of nanoparticles and the second plurality of nanoparticles comprises greater than 95% of the total nanoparticles formed of the first material in the first layer.

3. The method of claim **1**, wherein the first layer is formed by depositing a mixture that includes the first plurality of nanoparticles and the second plurality of nanoparticles.

4. The method of claim **1**, wherein the second average volume is at least two times the first average volume.

5. The method of claim **1**, wherein the second average volume is at least five times the first average volume.

6. The method of claim **1**, wherein the first layer is formed using an inkjet process.

7. The method of claim **1**, wherein the first plurality of nanoparticles and the second plurality of nanoparticles are formed an oxide.

8. A method of forming an optical device comprising:

forming a first layer over a plurality of optical structures, the first layer including a first plurality of nanoparticles and a second plurality of nanoparticles, wherein

the first plurality of nanoparticles are formed of a first material and the second plurality of nanoparticles are formed of a second material, and

the first plurality of nanoparticles and the second plurality of nanoparticles comprise greater than 95% of optically transparent nanoparticles in the first layer.

9. The method of claim **8**, wherein

the first material and the second material are formed of a same one or more chemical elements, and

the first material has a different chemical composition than the second material.

10. The method of claim **8**, wherein the second material includes at least one chemical element other than one or more chemical elements included in the first material.

11. The method of claim **8**, wherein

the first material consists of one or more chemical elements, and

the second material consists of one or more chemical elements that are each different from the one or more chemical elements that form the first material.

12. The method of claim **8**, wherein forming the first layer comprises curing a mixture that includes the first plurality of nanoparticles and the second plurality of nanoparticles after the mixture is deposited over the plurality of optical structures.

13. The method of claim **8**, wherein the first layer is formed by depositing a mixture that includes the first plurality of nanoparticles and the second plurality of nanoparticles.

14. The method of claim **8**, wherein the first layer is formed using an inkjet process.

15. A method of forming an optical device comprising:

forming a first layer over a plurality of optical structures, the first layer including a first plurality of nanoparticles and a second plurality of nanoparticles, wherein

the first plurality of nanoparticles have a different geometry than the second plurality of nanoparticles, and

the first plurality of nanoparticles and the second plurality of nanoparticles comprise greater than 95% of optically transparent nanoparticles in the first layer.

16. The method of claim **15**, wherein forming the first layer comprises curing a mixture that includes the first plurality of nanoparticles and the second plurality of nanoparticles after the mixture is deposited over the plurality of optical structures.

17. The method of claim **15**, wherein the first layer is formed by depositing a mixture that includes the first plurality of nanoparticles and the second plurality of nanoparticles.

18. The method of claim **15**, wherein the first layer is formed using an inkjet process.

19. The method of claim **15**, wherein

the first plurality of nanoparticles are formed of a rutile phase of titanium oxide, and

the second plurality of nanoparticles are formed of an anatase phase of titanium oxide.

20. The method of claim **15**, wherein the first plurality of nanoparticles have a crystalline structure and the second plurality of nanoparticles have an amorphous structure.

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