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Inventor(s)

SELL; David et al.

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## GRADIENT ENCAPSULATION OF WAVEGUIDE GRATINGS

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### Abstract

Embodiments described herein relate to gradient encapsulation of waveguide outcoupler gratings for control of diffraction efficiency and directionality. A device includes a first grating formed over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating corresponding to an outcoupler. The device includes a first encapsulant disposed in one or more gaps formed between adjacent first structures, where a fill ratio of the first encapsulant decreases along the first grating. Also described herein are methods for fabricating the device.

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**Inventors:** SELL; David (Santa Clara, CA), COHEN; Brian Alexander (Delmar, NY)

**Applicant:** Applied Materials, Inc. (Santa Clara, CA)

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation application of U.S. patent application Ser. No. 17/329,955, filed May 25, 2021, which claims the benefit of U.S. Provisional Patent Application Ser. No. 63/034,316, filed on Jun. 3, 2020, each of which is herein incorporated by reference.

### BACKGROUND

#### Field

[0002] Embodiments of the present disclosure generally relate to augmented reality waveguides. More specifically, embodiments described herein relate to gradient encapsulation of waveguide outcoupler gratings for control of diffraction efficiency and directionality.

#### 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 enhance or augment 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. Augmented waveguide combiners are used to assist in overlaying images. Generated light is in-coupled into an augmented waveguide combiner, propagated through the augmented waveguide combiner, out-coupled from the augmented waveguide combiner, and overlaid on the ambient environment. Light is coupled into and out of augmented waveguide combiners using surface relief gratings. The diffraction efficiency and directionality of the out-coupled light may not be adequately controlled.

[0006] Accordingly, what is needed in the art are improved waveguide combiners and methods of fabrication.

### SUMMARY

[0007] In one embodiment, a device is provided. The device includes a first grating formed over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating corresponding to an outcoupler. The device includes a first encapsulant disposed in one or more gaps formed between adjacent first structures, where a fill ratio of the first encapsulant decreases along the first grating.

[0008] In another embodiment, a device is provided. The device includes a first grating formed over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating corresponding to an outcoupler. The device includes a first encapsulant disposed in one or more first gaps formed between adjacent first structures, where a fill ratio of the first encapsulant decreases along the first grating. The device includes a second grating formed over the substrate, the second grating having a plurality of second structures extending away from the substrate, the second grating corresponding to an incoupler.

[0009] In yet another embodiment, a method is provided. The method includes forming a first grating over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating corresponding to an outcoupler. The method includes forming a

second grating over the substrate, the second grating having a plurality of second structures extending away from the substrate, the second grating corresponding to an incoupler. The method includes depositing a first encapsulant over the first and second gratings, curing the first encapsulant, and forming a patterned photoresist layer over the first and second gratings. The method includes etching the first encapsulant via the patterned photoresist layer, where a fill ratio of the first encapsulant decreases along the first grating and depositing a global encapsulant over the first and second gratings.

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## Description

### 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. 1A is a perspective, frontal view of a waveguide combiner according to an embodiment.

[0012] FIG. 1B is a schematic, cross-sectional view taken along line A-A' of FIG. 1A illustrating a waveguide combiner according to an embodiment.

[0013] FIG. 1C is a schematic, cross-sectional view taken along line A-A' of FIG. 1A illustrating a waveguide combiner according to another embodiment.

[0014] FIG. 1D is a schematic, cross-sectional view taken along line A-A' of FIG. 1A illustrating a waveguide combiner according to yet another embodiment.

[0015] FIG. 2 is a flow chart illustrating operations of a method for encapsulating waveguide gratings according to an embodiment.

[0016] FIGS. 3A-3J are schematic, cross-sectional views of a waveguide combiner during fabrication according to an embodiment.

[0017] FIG. 4 is a flow chart illustrating operations of a method encapsulating waveguide gratings according to another embodiment.

[0018] FIGS. 5A-5H are schematic, cross-sectional views of a waveguide combiner during fabrication according to another embodiment.

[0019] FIG. 6 is a flow chart illustrating operations of a method for encapsulating waveguide gratings according to yet another embodiment.

[0020] FIGS. 7A-7J are schematic, cross-sectional views of a waveguide combiner during fabrication according to yet another embodiment.

[0021] 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

[0022] Embodiments described herein relate to gradient encapsulation of waveguide outcoupler gratings for control of diffraction efficiency and directionality. A device includes a first grating formed over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating corresponding to an outcoupler. The device includes a first encapsulant disposed in one or more gaps formed between adjacent first structures, where a fill ratio of the first encapsulant decreases along the first grating. Also described herein are methods for fabricating the device.

[0023] FIG. 1A is a perspective, frontal view of an exemplary waveguide combiner **100** (e.g., for augmented reality (AR) applications). It is to be understood that the waveguide combiner **100** described below is an exemplary waveguide combiner that may be formed utilizing the systems and methods described herein, and that the systems and methods of the present disclosure may be utilized to form or modify other optical devices and nanostructured optical devices, such as other waveguide combiners. For example, an optical device having more than three gratings may be formed, such as five or more gratings. Alternatively, an optical device having less than three gratings may be formed, such as two gratings. In another example, an optical device having gratings on both major planar sides may be formed. In yet another example, an optical device having more than one input coupler and more than one output coupler may be formed.

[0024] The waveguide combiner **100** includes a first grating **110** corresponding to an incoupler, a second grating **120** corresponding to an outcoupler, and a third grating **130** between the incoupler and outcoupler. In some embodiments, the waveguide combiner **100** may include one or more additional gratings. Here, the third grating **130** is an intermediate grating for expanding the light between the first and second gratings **110**, **120**. It will be appreciated that the third grating **130** may be optional. In some embodiments, the first, second, and third gratings **110**, **120**, **130** are arranged so as to achieve substantially total internal reflection of light between the incoupler and outcoupler.

[0025] FIG. 1B is a schematic, cross-sectional view taken along line A-A' of FIG. 1A illustrating a waveguide combiner **100B** according to an embodiment. The waveguide combiner **100B** includes a substrate **102**. The substrate **102** may be formed from any suitable material and have any suitable thickness, provided that the substrate **102** can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the grating(s). In some embodiments, the material of the substrate **102** includes, but is not limited to, one or more of silicon (Si), silicon dioxide (SiO<sub>2</sub>), silicon carbide (SiC), glass, plastic, polycarbonate, and sapphire-containing materials. In some embodiments, the substrate **102** includes doped glass. For example, the substrate **102** includes glass doped with a heavy dopant such as lanthanum (La), zirconium (Zr), zinc (Zn), and the like. The materials of the substrate **102** may further have rollable and flexible properties. In some embodiments, the material of the substrate **102** includes, but is not limited to, materials having a refractive index between about 1.5 and about 2.4. For example, the substrate **102** may be a doped high index substrate having a refractive index between about 1.7 and about 2.4.

[0026] The waveguide combiner **100B** includes the first grating **110** and a second grating **120** disposed on the substrate **102**. In some embodiments, the first and second gratings **110**, **120** may be disposed on one or more spacer layers (not shown) disposed on the substrate **102**. In embodiments including a spacer layer, the spacer layer is operable to provide support for the first and second gratings **110**, **120** and is of a thickness and material according to the desired optical characteristics of the first and second gratings **110**, **120**. The first grating **110** includes a plurality of structures **112** extending above the substrate **102** and having gaps **114** formed between adjacent structures **112**. Likewise, the second grating **120** includes a plurality of structures **122** extending above the substrate **102** and having gaps **124** formed between sidewalls **126** of adjacent structures **122**. In some embodiments, the structures **112**, **122** may be fins. In some embodiments, the structures **112**, **122** may be disposed in the substrate **102**. In other words, the substrate **102** may be etched to form the structures **112**, **122** disposed therein.

[0027] In some embodiments, the structures **112**, **122** may be asymmetric (e.g., slanted or wedged). Here, the structures **112** are slanted opposite the structures **122**. In some other embodiments, the structures **112**, **122** may be slanted in the same direction. Here, the structures **112** are slanted left whereas the structures **122** are slanted right. However, the orientation of the structures **112**, **122** is not particularly limited to the illustrated embodiment. For example, the structures **112**, **122** may be slanted opposite relative to the depicted embodiment.

[0028] Here, the structures **122** are slanted at an angle  $\theta_1$  relative to the surface normal **106**, the slant angle  $\theta_1$  of each structure **122** being substantially the same. In another embodiment, the slant

angle  $\theta 1$  of one structure **122** may be different from the slant angle  $\theta 1$  of other structures **122**. In some embodiments, the slant angle  $\theta 1$  may be from about 30 degrees to about 60 degrees, such as from about 40 degrees to about 60 degrees, alternatively from about 30 degrees to about 40 degrees, alternatively from about 40 degrees to about 50 degrees, alternatively from about 50 degrees to about 60 degrees, such as about 50 degrees. In some embodiments, the slant angle  $\theta 1$  may be from about 0 degrees to about 30 degrees, such as from about 0 degrees to about 10 degrees, alternatively from about 10 degrees to about 20 degrees, alternatively from about 20 degrees to about 30 degrees. In some embodiments, the structures **122** may have a slant angle  $\theta 1$  equal to zero relative the surface normal **106**, and thus, the structures **122** may be binary structures. Here, each structure **122** has a single portion. In another embodiment, the structures **122** may have two or more portions having different slant angles relative to the surface normal **106**. In some embodiments, the material of the structures **122** is selected based on the desired depth and slant angle  $\theta 1$  of the structures **122**.

[0029] The gaps **124** have a depth **D1** defined as the distance from a surface **104** of the substrate **102** to a top surface **128** of the structures **122** and a width **W1** defined as the distance between sidewalls **126** of adjacent structures **122**. Here, the depth **D1** of each gap **124** is substantially the same. In another embodiment, the depth **D1** of at least one gap **124** may be different from the depth **D1** of other gaps **124**. Here, the width **W1** of each gap **124** is substantially the same. In another embodiment, the width **W1** of at least one gap **124** may be different from the width **W1** of other gaps **124**.

[0030] In some embodiments, one or more of the structures **112**, **122** can include structures having different geometries, such as different slant angles or dimensions from that of other structures in that grating. Additionally, a slant angle of one discrete structure within the plurality of structures **112**, **122** may be different across a length or width of the grating thereof.

[0031] The first and second gratings **110**, **120** independently include at least one of silicon oxycarbide (SiOC), titanium oxide (TiO.sub.x), TiO.sub.x nanomaterials, niobium oxide (NbO.sub.x), niobium-germanium (Nb.sub.3Ge), silicon dioxide (SiO.sub.2), silicon oxycarbonitride (SiOCN), vanadium (IV) oxide (VOx), aluminum oxide (Al.sub.2O.sub.3), indium tin oxide (ITO), zinc oxide (ZnO), tantalum pentoxide (Ta.sub.2O.sub.5), silicon nitride (Si.sub.3N.sub.4), Si.sub.3N.sub.4 silicon-rich, Si.sub.3N.sub.4 hydrogen-doped, Si.sub.3N.sub.4 boron-doped, silicon carbon nitrate (SiCN), titanium nitride (TiN), zirconium dioxide (ZrO.sub.2), germanium (Ge), gallium phosphide (GaP), poly-crystalline diamond (PCD), nanocrystalline diamond (NCD), and doped diamond containing materials. In some embodiments, the substrate **102** may be formed from any material included in the first and second gratings **110**, **120**, and vice versa. In some embodiments, the substrate **102** and the first and second gratings **110**, **120** may be formed from the same material(s).

[0032] The first and second gratings **110**, **120** may be formed over the surface of the substrate **102** by any suitable process. For example, the first and second gratings **110**, **120** may be formed by one or more of physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma-enhanced CVD (PECVD), flowable CVD (FCVD), atomic layer deposition (ALD), and spin-on processes.

[0033] In some embodiments, the material of the first and second gratings **110**, **120** may have a refractive index from about 1.5 to about 2.65, such as from about 1.5 to about 1.8, alternatively from about 2.2 to about 2.65, alternatively from about 1.8 to about 2.2, alternatively from about 1.8 to about 2, alternatively from about 2 to about 2.2, alternatively from about 1.9 to about 2.1, such as from about 1.9 to about 2, alternatively from about 2 to about 2.1, such as about 2.

[0034] In some embodiments, the waveguide combiner **100B** may include a grating material layer (not shown) disposed between the substrate **102** and the structures **112**, **122** of the first and second gratings **110**, **120**. The grating material layer may be formed of any suitable materials and by any suitable process including materials and processes used in forming the first and second gratings **110**, **120** described above.

[0035] The waveguide combiner **100B** includes a first encapsulant **140** disposed in the gaps **124** between the structures **122**. In some embodiments, the first encapsulant **140** may have a refractive index contrast of about 0.2 or less, such as from about 0 to about 0.2, such as from about 0 to about 0.05, alternatively from about 0.05 to about 0.1, alternatively from about 0.1 to about 0.15, alternatively from about 0.15 to about 0.2, alternatively about 0.1 or less, where the refractive index contrast is defined as the difference in refractive index between the first encapsulant **140** and the second grating **120**.

[0036] In some embodiments, the first encapsulant **140** may have a refractive index of from about 1.6 to about 2.4, such as from about 1.7 to about 2.3, such as from about 1.8 to about 2.2, such as from about 1.8 to about 2, such as from about 1.9 to about 2, such as from about 1.95 to about 2, alternatively from about 2 to about 2.2, such as from about 2 to about 2.1, such as from about 2 to about 2.05, such as about 2, alternatively from about 1.8 to about 1.85, alternatively from about 1.85 to about 1.9, alternatively from about 1.9 to about 1.95, alternatively from about 1.95 to about 1.96, alternatively from about 1.96 to about 1.97, alternatively from about 1.97 to about 1.98, alternatively from about 1.98 to about 1.99, alternatively from about 1.99 to about 2, alternatively from about 2 to about 2.01, alternatively from about 2.01 to about 2.02, alternatively from about 2.02 to about 2.03, alternatively from about 2.03 to about 2.04, alternatively from about 2.04 to about 2.05, alternatively from about 2.05 to about 2.1, alternatively from about 2.1 to about 2.2, alternatively from about 1.95 to about 2.05.

[0037] In some embodiments, the first encapsulant **140** includes at least one of polyimides, polyimide blends, metal-organic polyimide blends, metal oxides, metal nitrides, Al.sub.2O.sub.3, SiO.sub.2, TiO, TaO, AlN, SiN, SiO.sub.xN.sub.x, TiN, TaN, any of the materials forming the substrate **102**, any of the materials forming the first and second gratings **110**, **120**, and any other suitable materials having refractive indices according to the ranges set forth above. In some embodiments, the first encapsulant **140** includes any material having suitable gap fill properties and a refractive index from about 1.8 to about 2.2.

[0038] The first encapsulant **140** has a height H1 defined as the distance from the surface **104** of the substrate **102** to a top surface **142** of the encapsulant **140**. The first encapsulant **140** has a fill ratio defined as the ratio of the height H1 of the encapsulant **140** to the depth D1 of the second grating **120**. Here, the fill ratio decreases linearly from about 1 to about 0 along the second grating **120** from left to right. However, the profile of the first encapsulant **140** is not particularly limited to the illustrated embodiment. For example, in other embodiments, the fill ratio may decrease non-linearly (e.g., according to a power law function, exponential function, or another polynomial function). In some embodiments, the fill ratio may generally decrease while including one or more sections where the fill ratio is constant or even increasing. In some embodiments, the fill ratio may decrease stepwise (i.e., where each gap **124** has a constant fill ratio which is less than the preceding gap **124** and greater than the following gap **124**). In some embodiments, the fill ratio may be a combination of any of the above gradients.

[0039] In some embodiments, the fill ratio may have a maximum below 1 (i.e., where the encapsulant **140** is below the top surface **128**), such as from about 0.5 to about 1, such as from about 0.6 to about 1, such as from about 0.7 to about 1, such as from about 0.8 to about 1, such as from about 0.9 to about 1, alternatively from about 0.8 to about 0.9, alternatively from about 0.7 to about 0.8, alternatively from about 0.6 to about 0.7, alternatively from about 0.5 to about 0.6.

[0040] In some embodiments, the fill ratio may have a minimum above 0 (i.e., where the encapsulant **140** is present along the entire surface **104** of the second grating **120**), such as from about 0 to about 0.5, such as from about 0 to about 0.4, such as from about 0 to about 0.3, such as from about 0 to about 0.2, such as from about 0 to about 0.1, alternatively from about 0.1 to about 0.2, alternatively from about 0.2 to about 0.3, alternatively from about 0.3 to about 0.4, alternatively from about 0.4 to about 0.5.

[0041] In some embodiments, the fill ratio may range from about 0 to about 1, such as from about

0.1 to about 1, such as from about 0.2 to about 1, such as from about 0.3 to about 1, such as from about 0.4 to about 1, such as from about 0.5 to about 1, such as from about 0.6 to about 1, such as from about 0.7 to about 1, such as from about 0.8 to about 1, such as from about 0.9 to about 1, alternatively from about 0 to about 0.9, such as from about 0 to about 0.8, such as from about 0 to about 0.7, such as from about 0 to about 0.6, such as from about 0 to about 0.5, such as from about 0 to about 0.4, such as from about 0 to about 0.3, such as from about 0 to about 0.2, such as from about 0 to about 0.1.

[0042] Encapsulant gradients described herein enable control over diffraction efficiency along the second grating **120**. The low refractive index contrast of the encapsulant **140** (e.g., about 0.2 or less) decreases the diffraction efficiency compared to unencapsulated gratings (i.e., gratings without the encapsulant **140**). Unencapsulated gratings may have air (i.e., refractive index of 1) contacting the surface **104** or may include a global encapsulant having low refractive index (e.g., refractive index contrast greater than about 0.2). In some embodiments, the diffraction efficiency of the second grating **120** may be about 2.5% or less, alternatively from about 1% to about 50% such as from about 1% to about 40%, such as from about 1% to about 30%, such as from about 1% to about 20%, such as from about 1% to about 10%, such as from about 1% to about 5%, such as from about 1% to about 2.5%, alternatively from about 2.5% to about 5%, alternatively from about 5% to about 10%, alternatively from about 10% to about 20%, alternatively from about 20% to about 30%, alternatively from about 30% to about 40%, alternatively from about 40% to about 50%.

[0043] In addition to decreasing the diffraction efficiency, encapsulant gradients described herein control the diffraction efficiency along the second grating **120**. In some embodiments, as fill ratio increases, diffraction efficiency decreases. For example, as illustrated herein, the left end of the second grating **120** having the greatest fill ratio (i.e., 1) has the lowest diffraction efficiency (i.e. from about 1% to about 5%) and the right end of the second grating **120** having the lowest fill ratio (i.e., 0) has the greatest diffraction efficiency (i.e., from about 40% to about 50%). However, the orientation of the second grating **120** is not particularly limited to the illustrated embodiment. For example, the orientation may be such that the fill ratio of the second grating **120** decreases from right to left.

[0044] Conventional devices use shallow depth gratings to lower diffraction efficiency; however, shallow depth gratings limit directionality. Encapsulant gradients described herein can outcouple light at low efficiencies without reducing grating depth. Therefore, encapsulant gradients described herein can enable full-range tuning of diffraction efficiency while maintaining directionality towards the user over the entire surface of the second grating **120**. In one or more embodiments, the foregoing advantages compared to conventional devices may result from combining asymmetric structures **122** and encapsulant gradients.

[0045] The waveguide combiner **100B** includes a global encapsulant **150** over the first and second gratings **110**, **120** and the first encapsulant **140**. In some embodiments, the global encapsulant **150** may have a refractive index that is lower than that of the first and second gratings **110**, **120** and the first encapsulant **140**. In some embodiments, the refractive index of the global encapsulant **150** may be from about 1 to about 1.7, such as from about 1.2 to about 1.5. In some embodiments, the global encapsulant **150** may have an absorption coefficient less than about 0.001.

[0046] The global encapsulant **150** may be formed of any suitable transparent materials, including but not limited to silica-containing materials and non-silica-containing materials, such as polymer-containing materials, for example, fluoropolymer materials. In some embodiments, the global encapsulant **150** may be formed of silicon dioxide (SiO<sub>2</sub>) or low-k dielectric films such as carbon- and nitride-doped silicon oxide (SiCON) or silicon carbon nitride (SiCN). In some embodiments, the global encapsulant **150** may include fluorine-containing materials, such as aluminum fluoride (AlF<sub>3</sub>) and magnesium fluoride (MgF<sub>2</sub>).

[0047] FIG. **1C** is a schematic, cross-sectional view taken along line A-A' of FIG. **1A** illustrating a waveguide combiner **100C** according to another embodiment. The waveguide combiner **100C** is

similar to the waveguide combiner **100B** in most aspects, and the above description of the waveguide combiner **100B** may be incorporated herein without limitation.

[0048] In contrast to the waveguide combiner **100B**, the waveguide combiner **100C** includes the first encapsulant **140** over the first grating **110** in addition to the second grating **120**. The first encapsulant **140** is disposed in the gaps **114** between sidewalls **116** of adjacent structures **112**. Here, the first encapsulant **140** over the first grating **110** has a planar top surface **144**, which is higher than the top surface **142** of the first encapsulant **140** over the second grating **120**. In some embodiments, the top surface **144** may be non-planar. In some embodiments, the top surface **144** may be at or below the top surface **142**. Here, the top surface **144** is higher than a top surface **118** of the structures **112** such that the fill ratio of the gaps **114** is constant, being equal to 1. However, the profile of the first encapsulant **140** over the first grating **110** is not particularly limited to the illustrated embodiment. For example, the fill ratio may be less than 1. In such embodiments, the fill ratio may vary along the first grating **110**.

[0049] The waveguide combiner **100C** includes the global encapsulant **150**. Here, the global encapsulant **150** contacts the top surface **144** of the first encapsulant **140** over the first grating **110**.

[0050] FIG. **1D** is a schematic, cross-sectional view taken along line A-A' of FIG. **1A** illustrating a waveguide combiner **100D** according to yet another embodiment. The waveguide combiner **100D** is similar to the waveguide combiners **100B** and/or **100C** in most aspects, and the above description of the waveguide combiners **100B**, **100C** may be incorporated herein without limitation.

[0051] In contrast to the waveguide combiners **100B**, **100C**, the waveguide combiner **100D** has dual-sided gratings, where dual-sided gratings are defined as being on opposite planar sides of the substrate **102**. Here, the first grating **110** is disposed on a backside surface **108** of the substrate **102** opposite of the frontside surface **104** on which the second grating **120** is disposed. The waveguide combiner **100D** includes a second encapsulant **146** over the first and second gratings **110**, **120** on the backside surface **108**. The second encapsulant **146** is disposed in the gaps **114** between sidewalls **116** of adjacent structures **112** of the first grating **110**. The second encapsulant **146** has a surface **148** facing away from the backside **108** of the substrate **102**. The second encapsulant **146** may be the same or different from the first encapsulant **140**, and the above description of the first encapsulant **140** may be incorporated herein without limitation.

[0052] Here, the second encapsulant **146** covers the backside **108** over the first and second gratings **110**, **120**. However, the second encapsulant **146** is not particularly limited to the illustrated embodiment. For example, the second encapsulant **146** may only cover the backside **108** over the first grating **110**. In some other embodiments, the second encapsulant **146** may be omitted.

[0053] The waveguide combiner **100D** includes the global encapsulant **150**. Here, the global encapsulant **150** contacts the surface **148** of the second encapsulant **146** over the first and second gratings **110**, **120**.

[0054] FIG. **2** is a flow chart illustrating operations of a method **200** for encapsulating waveguide gratings according to an embodiment. FIGS. **3A-3J** are schematic, cross-sectional views of a waveguide combiner **100B** during fabrication according to an embodiment.

[0055] Referring to FIGS. **2** and **3A**, at step **202**, the method **200** includes forming the first grating **110** corresponding to an incoupler and the second grating **120** corresponding to an outcoupler. The first and second gratings **110**, **120** may be formed using any of the materials and processes described above.

[0056] Referring to FIGS. **2** and **3B**, at step **204**, the method **200** includes depositing the first encapsulant **140** over the first and second gratings **110**, **120**. The first encapsulant **140** is deposited over the surface **104** of the substrate **102**, in the gaps **114**, **124**, over the structures **112**, and along the sidewalls **126** and top surfaces **128** of the structures **122**. The first encapsulant **140** may be formed by any suitable process. For example, the first encapsulant **140** may be formed by one or more of PVD, CVD, PECVD, FCVD, ALD, and spin-on processes.



[0057] Referring to FIGS. 2 and 3B, at step 206, the method 200 includes curing the first encapsulant 140. In some embodiments, the first encapsulant 140 may be cured by heat, pressure, chemical treatment, or any other suitable curing technique.

[0058] Referring to FIGS. 2 and 3C, at step 208, the method 200 includes depositing a first hardmask layer 162 over the cured first encapsulant 140. The first hardmask layer 162 includes at least one of titanium nitride, silicon nitride, and silicon carbide. The first hardmask layer 162 may be formed by any suitable process. For example, the first hardmask layer 162 may be formed by one or more of PVD, CVD, PECVD, FCVD, ALD, and spin-on processes.

[0059] Referring to FIGS. 2 and 3D, at step 210, the method 200 includes forming a patterned second hardmask layer 164 over the first hardmask layer 162. The patterned second hardmask layer 164 is disposed over the second grating 120 but not over the first grating 110. Thus, the patterned second hardmask layer 164 can be used as an etch mask for etching the first hardmask layer 162 over the first grating 110. The patterned second hardmask layer 164 includes at least one of a positive or negative tone photoresist, a metal-containing hardmask, a carbon-containing hardmask, an organic planarization layer (OPL), and other suitable hardmask materials. The patterned second hardmask layer 164 may be formed by any suitable process. For example, the patterned second hardmask layer 164 may be formed by one or more of PVD, CVD, PECVD, FCVD, ALD, and spin-on processes.

[0060] Referring to FIGS. 2 and 3E, at step 212, the method 200 includes removing the first hardmask layer 162 over the first grating 110. The first hardmask layer 162 may be removed by an etching process having etch selectivity for the first hardmask layer 162 relative to the patterned second hardmask layer 164. Thus, the first hardmask layer 162 may be removed from over the first grating 110 without affecting the patterned second hardmask layer 164 and/or the first hardmask layer 162 over the second grating 120. The etching process can include at least one of wet etching, dry etching, reactive ion etching, and plasma etching.

[0061] Referring to FIGS. 2 and 3F, at step 214, the method 200 includes etching the first encapsulant 140 over the first grating 110. The first hardmask layer 162 over the second grating 120 may be used as an etch mask for etching the first encapsulant 140 over the first grating 110. The first encapsulant 140 may be removed by an etching process having etch selectivity for the first encapsulant 140 relative to one of the patterned second hardmask layer 164 or the first hardmask layer 162. Thus, the first encapsulant 140 may be removed from over the first grating 110 without affecting the first encapsulant 140 over the second grating 120. The etching process can include at least one of wet etching, dry etching, reactive ion etching, and plasma etching.

[0062] Referring to FIGS. 2 and 3G, at step 216, the method 200 includes removing the first hardmask layer 162 over the second grating 120. The first hardmask layer 162 may be removed from over the second grating 120 to prepare the encapsulant 140 over the second grating 120 for a subsequent etching step. The first hardmask layer 162 may be removed by at least one of stripping, wet etching, dry etching, reactive ion etching, and plasma etching.

[0063] Referring to FIGS. 2 and 3H, at step 218, the method 200 includes forming a patterned photoresist layer 166 over the first and second gratings 110, 120. In some embodiments, the patterned photoresist layer 166 may be formed by any suitable lithography process (e.g., a gray-scale lithography process using scanning gray tone exposure where dosage is increased during scanning across the waveguide combiner 100B from the first grating 110 to the second grating 120). A gray-scale lithography process may include blanket depositing a photoresist material over the first and second gratings 110, 120. Here, the photoresist material contacts the first grating 110 and the first encapsulant 140 over the second grating 120. In some embodiments, the photoresist material may include but is not limited to, light-sensitive polymer containing materials.

[0064] Subsequently, exposure of the photoresist material may include using a gradient of exposure dosage along the photoresist material to form a latent pattern therein. In some embodiments, the latent pattern may include, but is not limited to, any one-, two-, or three-dimensional shape created

in the photoresist material using lithography or laser ablation. In some embodiments, the latent pattern may be graded. The shape of the latent pattern may determine a profile of the first encapsulant **140**. After forming the latent pattern, the photoresist material may be developed to form the patterned photoresist layer **166** shown in FIG. **3H**. The photoresist material may be a positive tone photoresist such that the exposed regions of the photoresist material are removed during development. In some embodiments, developing the photoresist material may include performing a lithography process, such as photolithography, digital lithography, or by performing laser ablation.

[0065] Here, the patterned photoresist layer **166** has a thickness **T1** measured above the first encapsulant **140** that decreases linearly along the first and second gratings **110**, **120**. However, the profile of the patterned photoresist layer **166** is not particularly limited to the illustrated embodiment. For example, the profile may decrease non-linearly (e.g., according to a power law function, exponential function, or another polynomial function), the profile may generally decrease while including one or more sections where the profile is constant or even increasing, the profile may decrease stepwise, or the profile may be a combination of any of the above profiles. The profile of the patterned photoresist layer **166** may be transferred to the first encapsulant **140** during subsequent etching.

[0066] Referring to FIGS. **2** and **3I**, at step **220**, the method **200** includes etching the patterned photoresist layer **166** and the first encapsulant **140**. Here, the etching process exposes portions of the sidewalls **126** and the top surfaces **128** of the structures **122**. The etching process can include any suitable directional or non-directional etching process. In some embodiments, the profile of the patterned photoresist layer **166** may be transferred to the first encapsulant **140** by an isotropic etching process. The isotropic etching process may have etch selectivity for the patterned photoresist layer **166** and the first encapsulant **140** relative to the structures **122** such that the first encapsulant **140** may be etched without affecting the underlying structures **122**. Here, the patterned photoresist layer **166** and the first encapsulant **140** are removed at substantially the same rate such that the profile of the etched first encapsulant **140** substantially matches the profile of the patterned photoresist layer **166**. In some other embodiments, the profile of the etched first encapsulant **140** may differ from the profile of the patterned photoresist layer **166** depending on differences in etch rate or etch selectivity.

[0067] In some embodiments, directional etching may be used with or without a gradient formed in the patterned photoresist layer **166**. In some embodiments, the top surface **142** of the etched first encapsulant **140** may be perpendicular to the sidewalls **126** of the structures **122**. In some embodiments, the etching process may form a stepwise decrease in the etched first encapsulant **140** such that the top surface **142** between adjacent structures **122** is substantially parallel to the surface **104** of the substrate **102**.

[0068] In some embodiments, the etching process can include a cyclic etching process using one or more proximity masks. In some embodiments, the etching may be uniform. In some other embodiments, the etching may be selective. In some embodiments, a single etch chemistry may be used. In some other embodiments, two or more different etch chemistries may be used.

[0069] Referring to FIGS. **2** and **3J**, at step **222**, the method **200** includes depositing the global encapsulant **150** over the first and second gratings **110**, **120**. The global encapsulant **150** is deposited over the surface **104** of the substrate **102**, in the gaps **114**, over the structures **112**, over the etched first encapsulant **140**, and along the exposed sidewalls **126** and top surfaces **128** of the structures **122**. The global encapsulant **150** may be formed by any suitable process. For example, the global encapsulant **150** may be formed by one or more of PVD, CVD, PECVD, FCVD, ALD, and spin-on processes.

[0070] FIG. **4** is a flow chart illustrating operations of a method **400** for encapsulating waveguide gratings according to an embodiment. FIGS. **5A-5H** are schematic, cross-sectional views of a waveguide combiner **100C** during fabrication according to an embodiment.

[0071] Referring to FIGS. 4 and 5A, at step 402, the method 400 includes forming the first grating 110 corresponding to an incoupler and forming the second grating 120 corresponding to an outcoupler. Referring to FIGS. 4 and 5B, at step 404, the method 400 includes depositing the first encapsulant 140 over the first and second gratings 110, 120. Referring to FIGS. 4 and 5B, at step 406, the method 400 includes curing the first encapsulant 140. Referring to FIGS. 4 and 5C, at step 408, the method 400 includes depositing a first hardmask layer 172 over the cured first encapsulant 140. Steps 402 through 408 are analogous to steps 202 through 208 of the method 200.

[0072] Referring to FIGS. 4 and 5D, at step 410, the method 400 includes forming a patterned second hardmask layer 174 over the first hardmask layer 172. Step 410 is analogous to step 210 of the method 200 except that the patterned second hardmask layer 174 is disposed over the first grating 110 but not over the second grating 120. Thus, the patterned second hardmask layer 174 can be used as an etch mask for etching the first hardmask layer 172 over the second grating 120.

[0073] Referring to FIGS. 4 and 5E, at step 412, the method 400 includes removing the first hardmask layer 172 over the second grating 120. Step 412 is analogous to step 216 of the method 200 except that the first hardmask layer 172 remains disposed over the first grating 110.

[0074] Referring to FIGS. 4 and 5F, at step 414, the method 400 includes forming a patterned photoresist layer 176 over the first and second gratings 110, 120. Step 414 is analogous to step 218 of the method 200 except that the photoresist material contacts the first hardmask layer 172 over the first grating 110 and the first encapsulant 140 over the second grating 120. After forming the latent pattern, the photoresist material may be developed to form the patterned photoresist layer 176 shown in FIG. 5F.

[0075] Referring to FIGS. 4 and 5G, at step 416, the method 400 includes etching the patterned photoresist layer 176 and the first encapsulant 140. Step 416 is analogous to step 220 of the method 200 except that the first hardmask layer 172 remaining over the first grating 110 is used as an etch mask for etching the first encapsulant 140 over the second grating 120 without affecting the first encapsulant 140 over the first grating 110.

[0076] Referring to FIGS. 4 and 5H, at step 418, the method 400 includes depositing the global encapsulant 150 over the first and second gratings 110, 120. Step 418 is analogous to step 222 of the method 200 except that the global encapsulant 150 is disposed on the top surface 144 of the first encapsulant 140 over the first grating 110.

[0077] FIG. 6 is a flow chart illustrating operations of a method 600 for encapsulating waveguide gratings according to an embodiment. FIGS. 7A-7J are schematic, cross-sectional views of a waveguide combiner 100D during fabrication according to an embodiment.

[0078] Referring to FIGS. 6 and 7A, at step 602, the method 600 includes forming the first grating 110 corresponding to an incoupler on the backside 108 of the substrate 102 and the second grating 120 corresponding to an outcoupler on the frontside 104 facing opposite the backside 108 of the substrate 102. Step 602 is analogous to step 202 of the method 200 except that the first grating 110 is formed on the backside 108 of the substrate 102.

[0079] Referring to FIGS. 6 and 7B, at step 604, the method 600 includes depositing the first encapsulant 140 on the frontside 104. Step 604 is analogous to step 204 of the method 200 except that the first encapsulant 140 is deposited over the surface 104 of the substrate 102, in the gaps 124, and along the sidewalls 126 and top surfaces 128 of the structures 122.

[0080] Referring to FIGS. 6 and 7B, at step 606, the method 600 optionally includes depositing the second encapsulant 146 on the backside 108. The second encapsulant 146 is deposited over the backside surface 108 of the substrate 102, in the gaps 114 and over the structures 112. The second encapsulant 146 has a surface 148 facing away from the backside 108 of the substrate 102. The second encapsulant 146 may be formed by any suitable process. For example, the second encapsulant 146 may be formed by one or more of PVD, CVD, PECVD, FCVD, ALD, and spin-on processes.

[0081] Referring to FIGS. 6 and 7B, at step 608, the method 600 includes curing the first

encapsulant **140** and the optional second encapsulant **146**. Step **608** is analogous to step **206** of the method **200** except that the curing process may be applied to the frontside **104** and backside **108** of the substrate **102**.

[0082] Referring to FIGS. **6** and **7C**, at step **610**, the method **600** includes depositing a first hardmask layer **182** over the cured first encapsulant **140** on the frontside **104**. Referring to FIGS. **6** and **7D**, at step **612**, the method **600** includes forming a patterned second hardmask layer **184** over the first hardmask layer **182** on the frontside **104**. Referring to FIGS. **6** and **7E**, at step **614**, the method **600** includes removing the first hardmask layer **182** over the first grating **110** on the frontside **104**. Referring to FIGS. **6** and **7F**, at step **616**, the method **600** includes etching the first encapsulant **140** over the first grating **110** on the frontside **104**. Referring to FIGS. **6** and **7G**, at step **618**, the method **600** includes removing the first hardmask layer **182** over the second grating **120** on the frontside **104**. Referring to FIGS. **6** and **7H**, at step **620**, the method **600** includes forming a patterned photoresist layer **186** over the first and second gratings **110**, **120** on the frontside **104**. Referring to FIGS. **6** and **7I**, at step **622**, the method **600** includes etching the patterned photoresist layer **186** and the first encapsulant **140** on the frontside **104**. Steps **610** through **622** are analogous to steps **208** through **220** of the method **200** except that the waveguide combiner **100D** has the first grating **110** on the backside **108**.

[0083] Referring to FIGS. **6** and **7J**, at step **624**, the method **600** includes depositing the global encapsulant **150** over the first and second gratings **110**, **120** on the frontside **104** and backside **108**. Step **624** is analogous to step **222** of the method **200** except that the global encapsulant **150** is disposed over the frontside **104** and backside **108**. The global encapsulant **150** is disposed on the surface **148** of the second encapsulant **146** over the first and second gratings **110**, **120**.

[0084] While the foregoing is directed to examples of the present disclosure, other and further examples of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

## Claims

1. A waveguide combiner comprising: a first grating formed over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating corresponding to an outcoupler; and a first encapsulant disposed in one or more gaps formed between adjacent first structures, wherein a fill ratio of the first encapsulant varies along the first grating in a direction from a first structure at one side of the first grating to another first structure at an opposite side of the first grating.
2. The waveguide combiner of claim 1, wherein the first encapsulant has a refractive index contrast of about 0.2 or less relative to the first grating.
3. The waveguide combiner of claim 1, wherein the first encapsulant has a refractive index of from about 1.8 to about 2.2.
4. The waveguide combiner of claim 1, wherein the first encapsulant includes or more of polyimides, polyimide blends, or metal-organic polyimide blends.
5. The waveguide combiner of claim 1, wherein the fill ratio of the first encapsulant ranges from about 0 to about 1.
6. The waveguide combiner of claim 1, wherein the fill ratio varies linearly.
7. The waveguide combiner of claim 1, wherein the fill ratio varies stepwise.
8. The waveguide combiner of claim 1, wherein the fill ratio varies non-linearly.
9. The waveguide combiner of claim 1, further comprising a second grating formed over the substrate, the second grating having a plurality of second structures extending away from the substrate, the second grating corresponding to an incoupler.
10. A waveguide combiner comprising: a first grating formed over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating

corresponding to an outcoupler; a first encapsulant disposed in one or more first gaps formed between adjacent first structures, wherein a fill ratio of the first encapsulant varies along the first grating in a direction from a first structure at one side of the first grating to another first structure at an opposite side of the first grating; and a second grating formed over the substrate, the second grating having a plurality of second structures extending away from the substrate, the second grating corresponding to an incoupler.

**11.** The waveguide combiner of claim 10, wherein the first encapsulant is disposed in one or more second gaps formed between adjacent second structures.

**12.** The waveguide combiner of claim 10, wherein the first and second gratings are formed on a frontside of the substrate.

**13.** The waveguide combiner of claim 10, wherein the first grating is formed on a frontside of the substrate, and wherein the second grating is formed on a backside of the substrate facing opposite the frontside.

**14.** The waveguide combiner of claim 13, further comprising a second encapsulant disposed over the backside of the substrate, wherein the second encapsulant is disposed in one or more second gaps formed between adjacent second structures.

**15.** A method of fabricating a waveguide combiner, comprising: forming a first grating over a substrate, the first grating having a plurality of first structures extending away from the substrate, the first grating corresponding to an outcoupler; forming a second grating over the substrate, the second grating having a plurality of second structures extending away from the substrate, the second grating corresponding to an incoupler; depositing a first encapsulant over the first and second gratings; curing the first encapsulant; forming a patterned photoresist layer over the first and second gratings; etching the first encapsulant via the patterned photoresist layer, wherein a fill ratio of the first encapsulant varies along the first grating in a direction from a first structure at one side of the first grating to another first structure at an opposite side of the first grating; and depositing a global encapsulant over the first and second gratings.

**16.** The method of claim 15, further comprising: depositing a first hardmask layer over the cured first encapsulant; and forming a patterned second hardmask layer over the first hardmask layer.

**17.** The method of claim 16, further comprising: removing the first hardmask layer over the second grating; and etching the first encapsulant over the second grating using one of the patterned second hardmask layer or the first hardmask layer as an etch mask.

**18.** The method of claim 15, wherein forming the patterned photoresist layer comprises performing a gray-scale lithography process.

**19.** The method of claim 15, wherein etching the first encapsulant via the patterned photoresist layer comprises transferring a profile of the patterned photoresist layer to the first encapsulant.

**20.** The method of claim 15, wherein the first grating is formed on a frontside of the substrate, wherein the first encapsulant is deposited on the frontside, and wherein the second grating is formed on a backside of the substrate facing opposite the frontside, further comprising depositing a second encapsulant on the backside.

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