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(54) **DIRECT BONDING USING LOW INDEX FILM AND LAMINATION FOR WAVEGUIDE**

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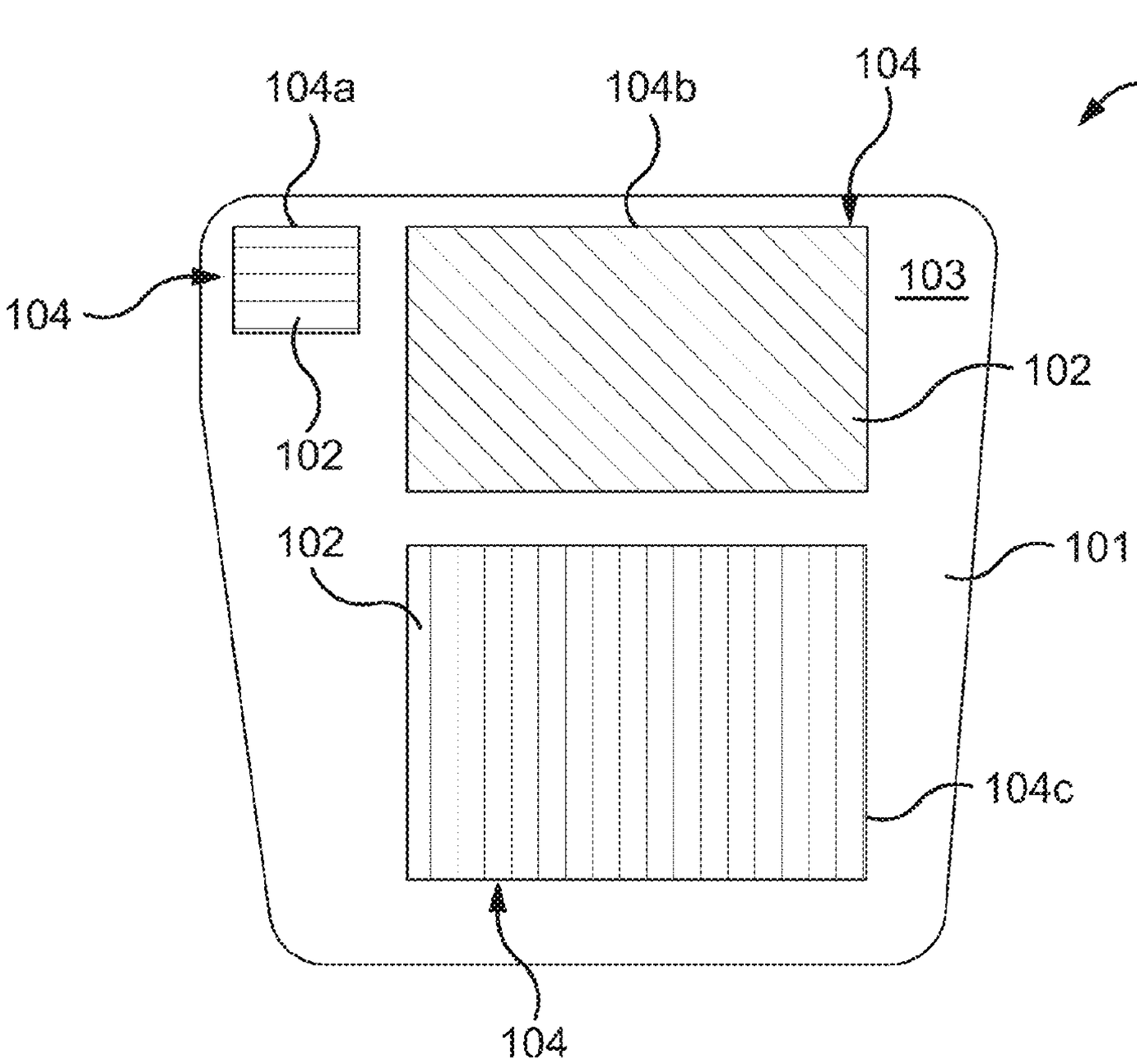
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(57) **ABSTRACT**

Embodiments of the present invention relate to waveguide and methods of forming waveguides. The waveguide includes a waveguide stack including a waveguide substrate having a top surface and a bottom surface, a first low index layer disposed on the top surface, a first cap layer disposed on the first low index layer, a first lens disposed on the first cap layer, and a first optically clear adhesive layer between the first low index layer and the first lens. In another embodiment, a method of forming a waveguide is provided. The method includes dispensing a liquid optically clear adhesive layer on a lens, placing a waveguide stack including a first low index layer onto the liquid optically clear adhesive opposite the lens, and curing the liquid optically clear adhesive. The waveguide stack further includes a first cap layer disposed on the first low index layer.



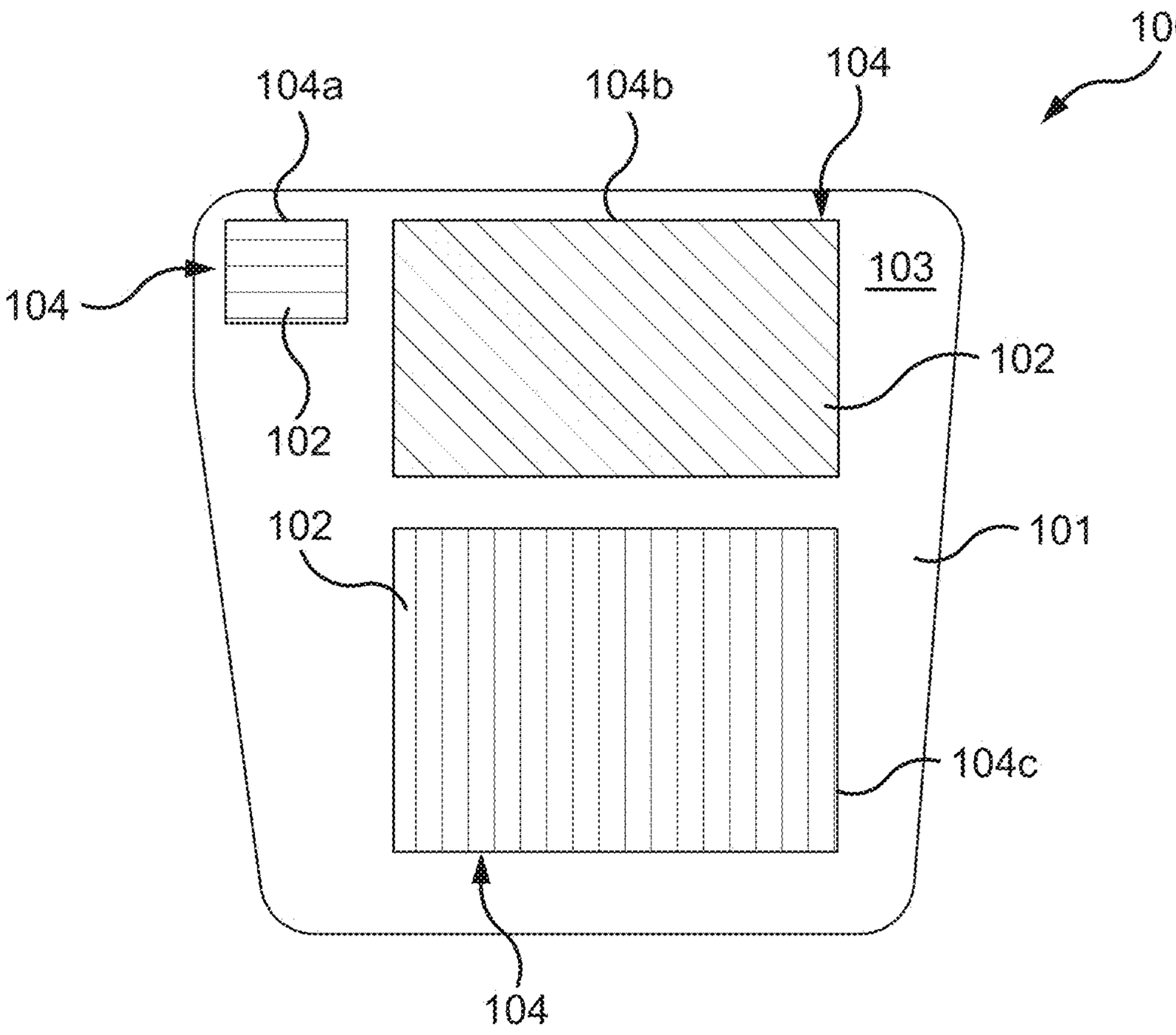


FIG. 1

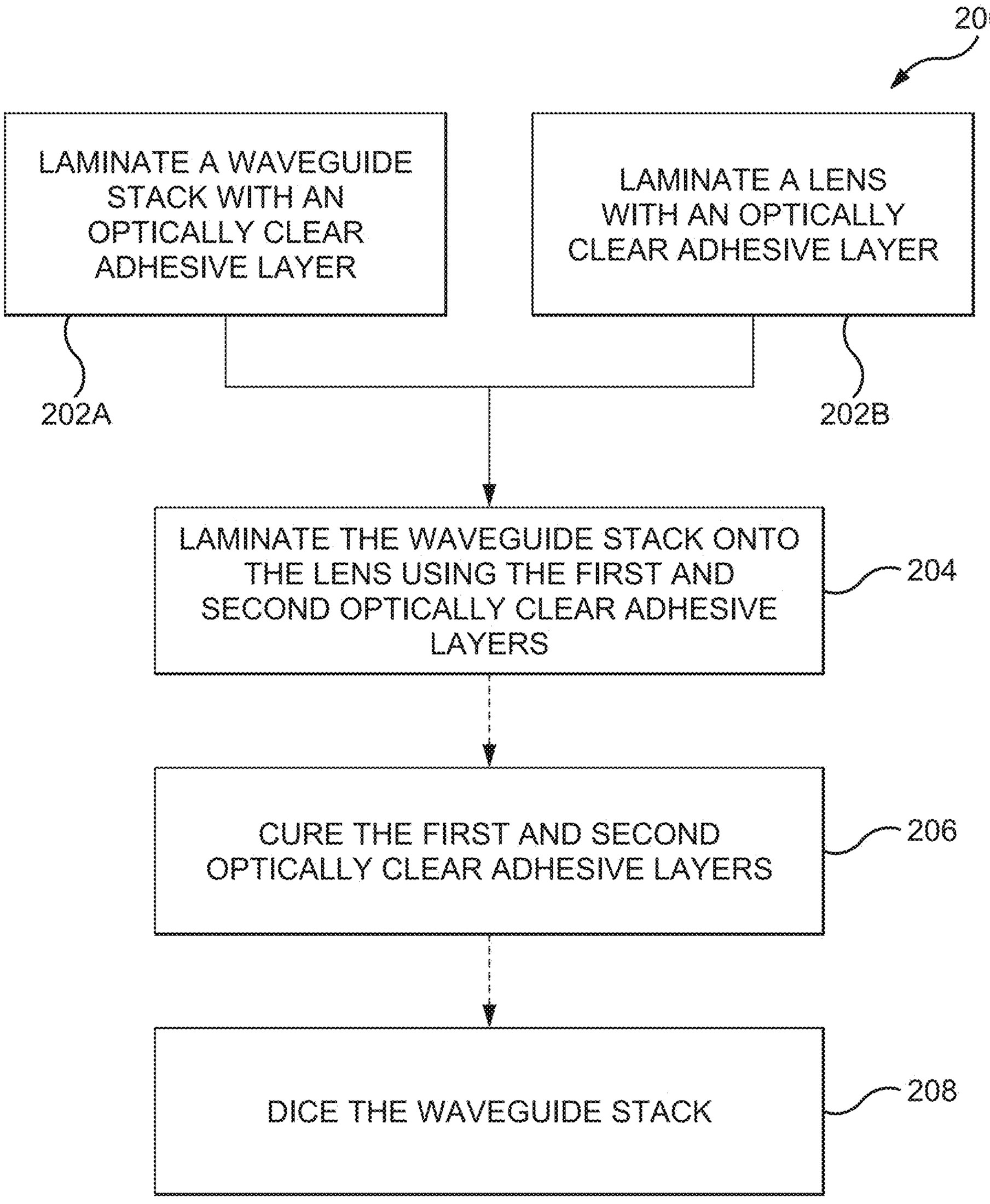

200
LAMINATE A WAVEGUIDE STACK WITH AN OPTICALLY CLEAR ADHESIVE LAYER
LAMINATE A LENS WITH AN OPTICALLY CLEAR ADHESIVE LAYER
202A
202B
LAMINATE THE WAVEGUIDE STACK ONTO THE LENS USING THE FIRST AND SECOND OPTICALLY CLEAR ADHESIVE LAYERS
204
CURE THE FIRST AND SECOND OPTICALLY CLEAR ADHESIVE LAYERS
206
DICE THE WAVEGUIDE STACK
208

FIG. 2

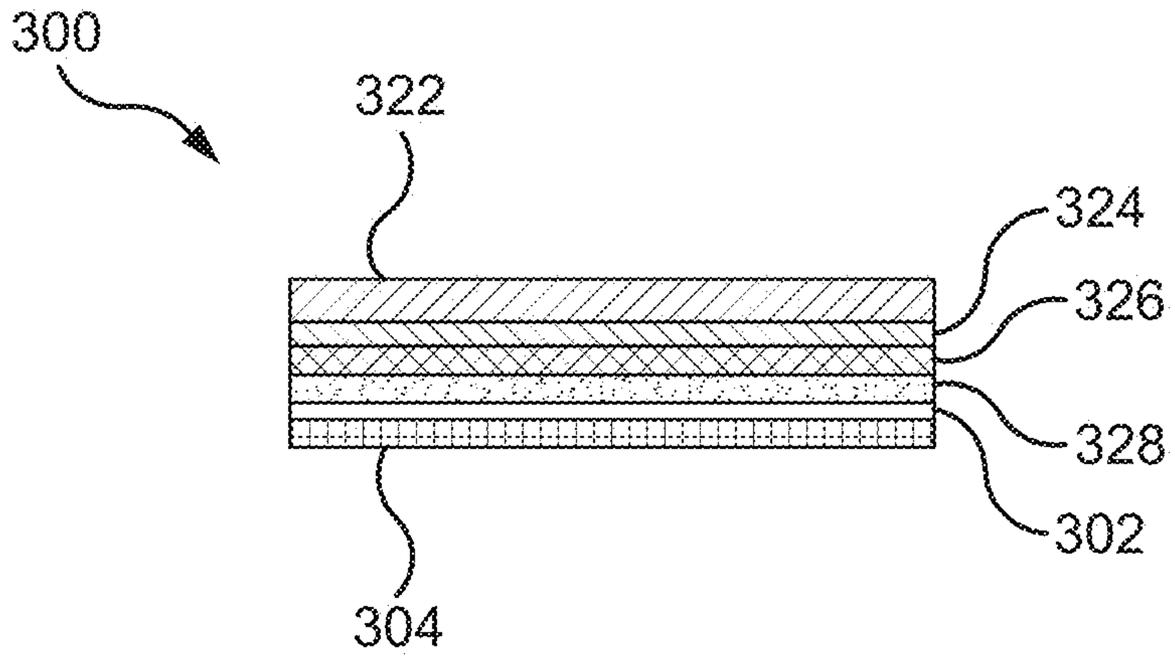


FIG. 3A

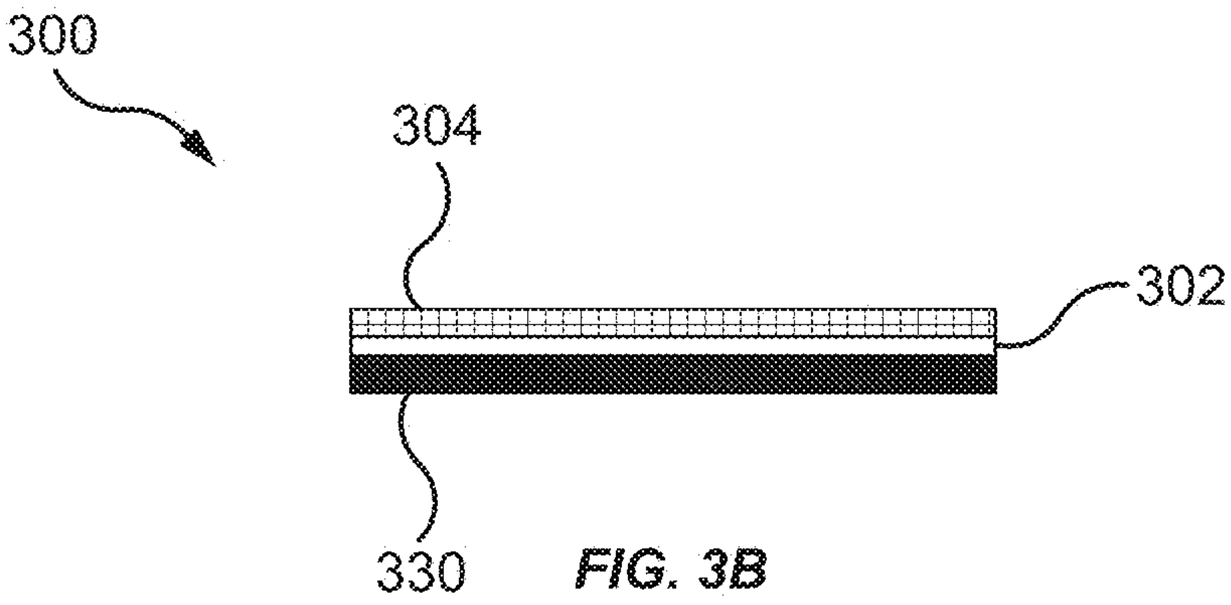


FIG. 3B

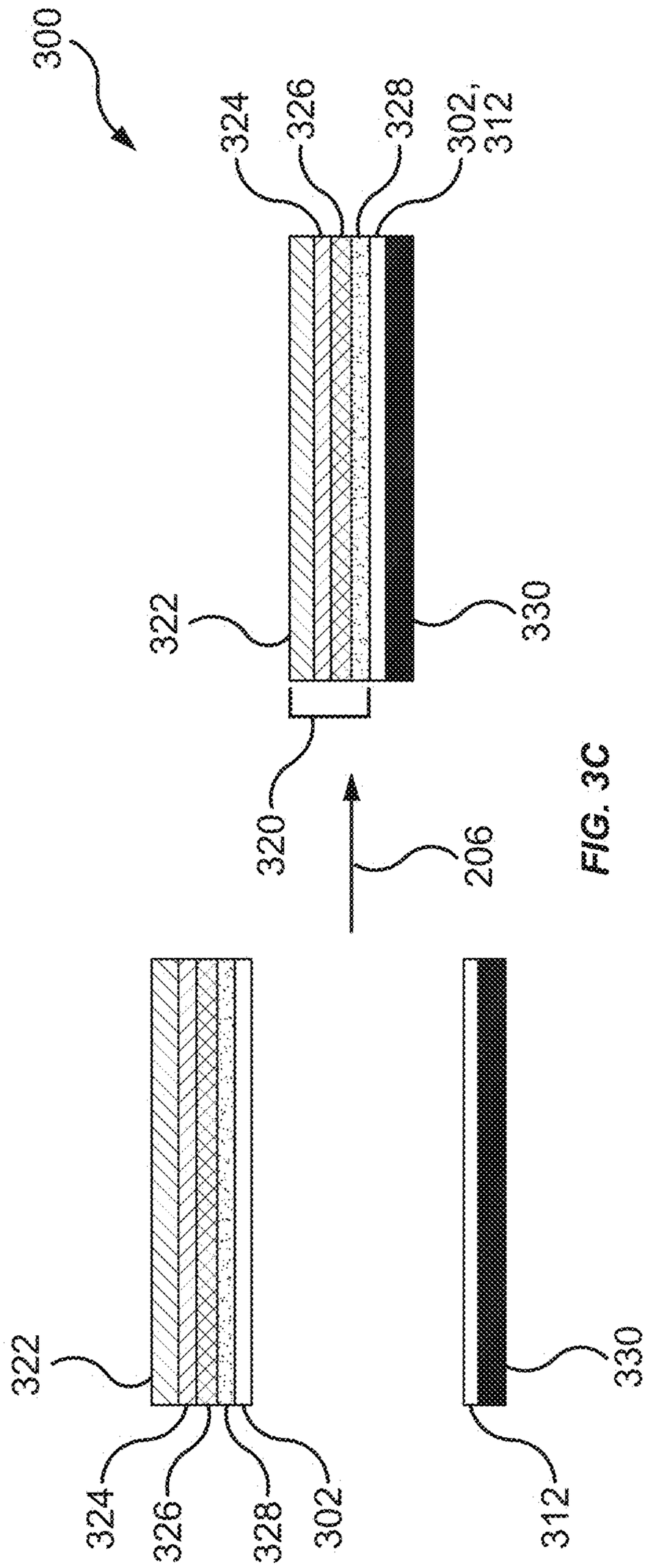

300
324
326
328
302, 312
322
330
320
206
322
324
326
328
302
312
330

FIG. 3C

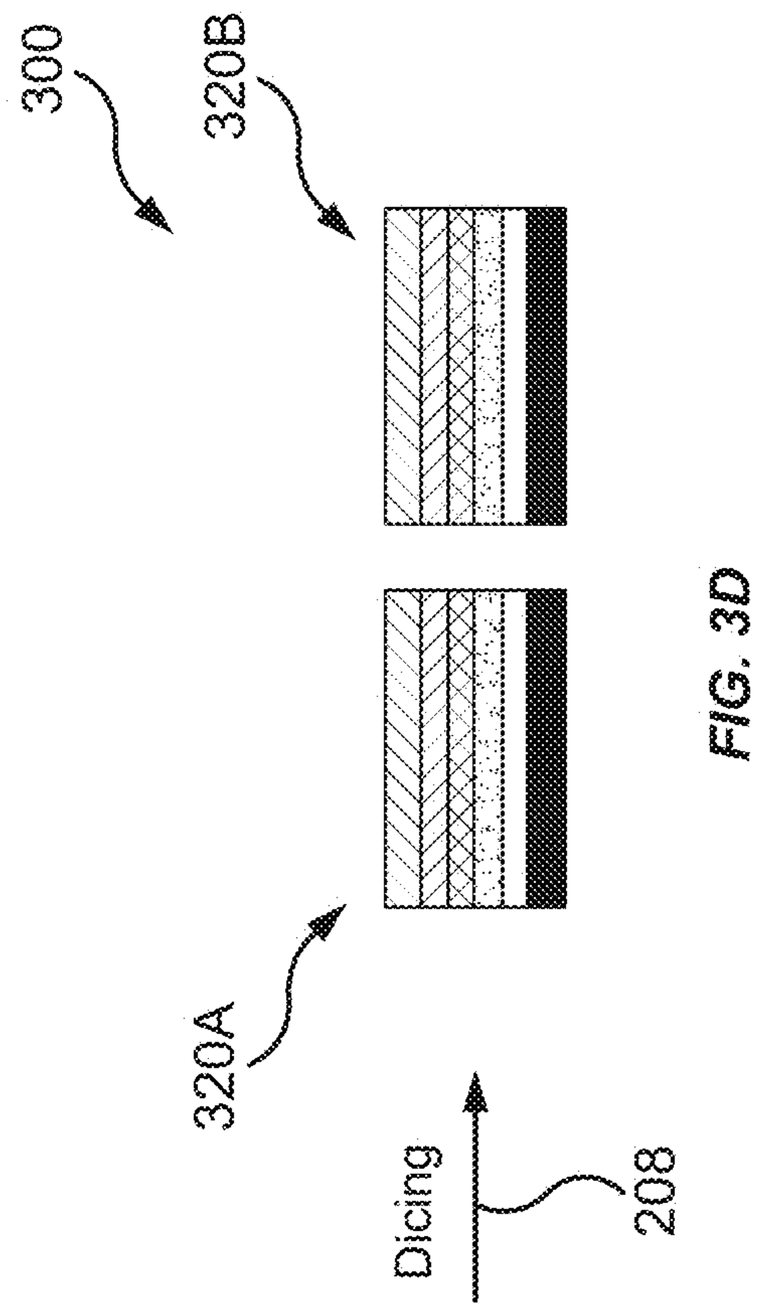

300
320B
320A
Dicing
208

FIG. 3D

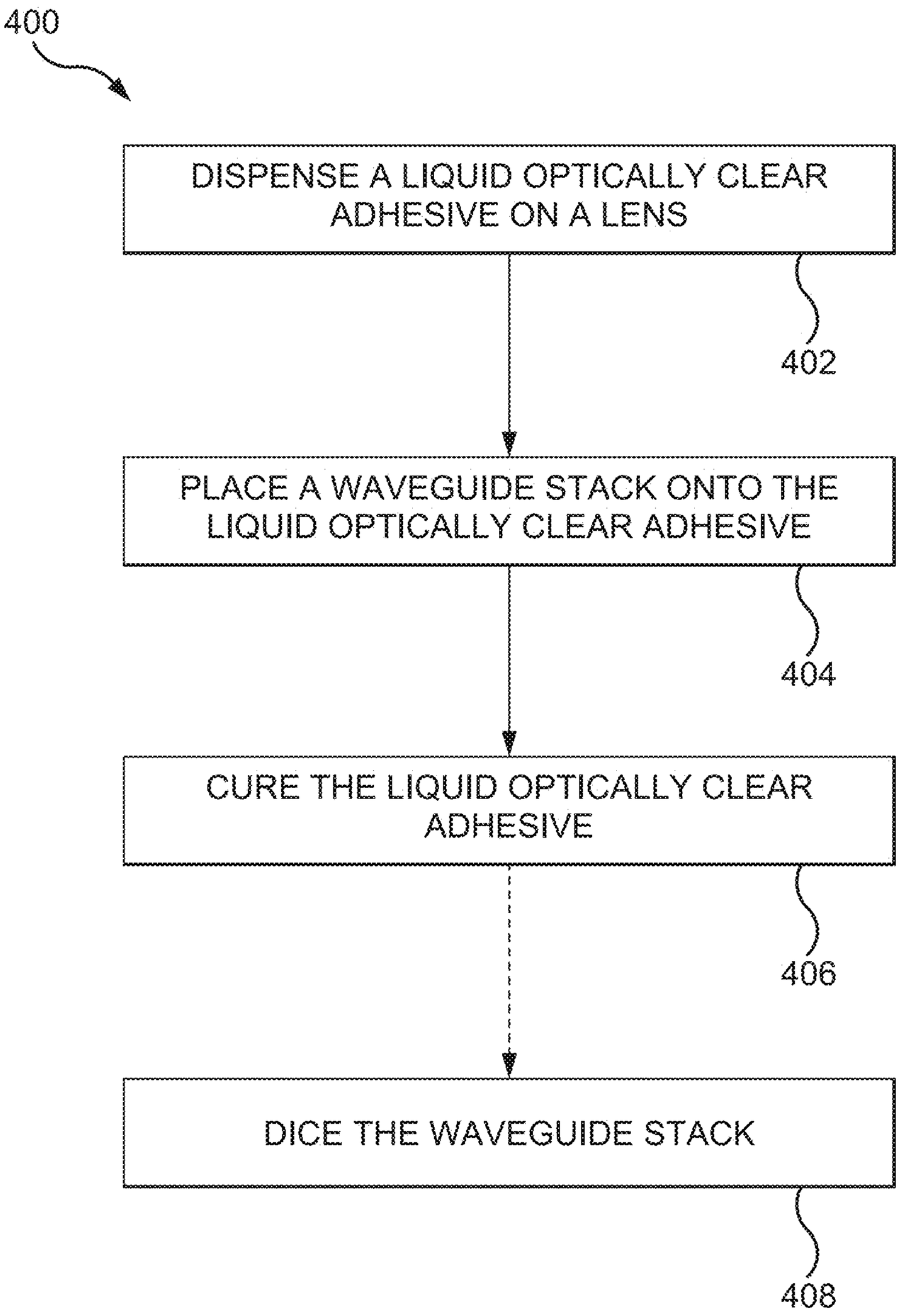

400
DISPENSE A LIQUID OPTICALLY CLEAR ADHESIVE ON A LENS
402
PLACE A WAVEGUIDE STACK ONTO THE LIQUID OPTICALLY CLEAR ADHESIVE
404
CURE THE LIQUID OPTICALLY CLEAR ADHESIVE
406
DICE THE WAVEGUIDE STACK
408

FIG. 4

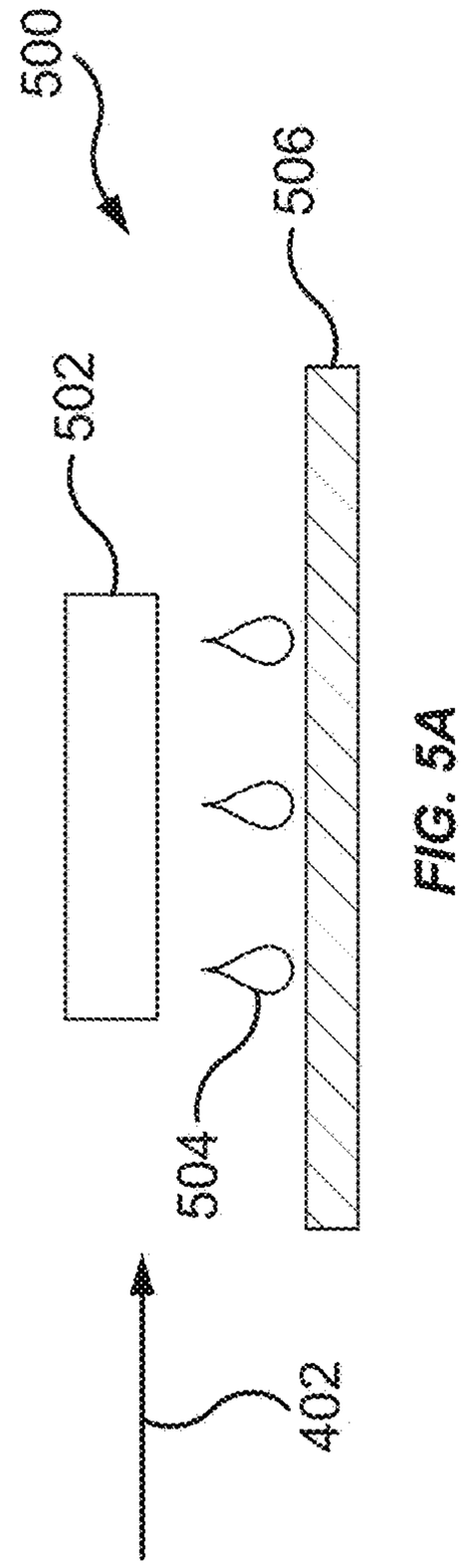


FIG. 5A

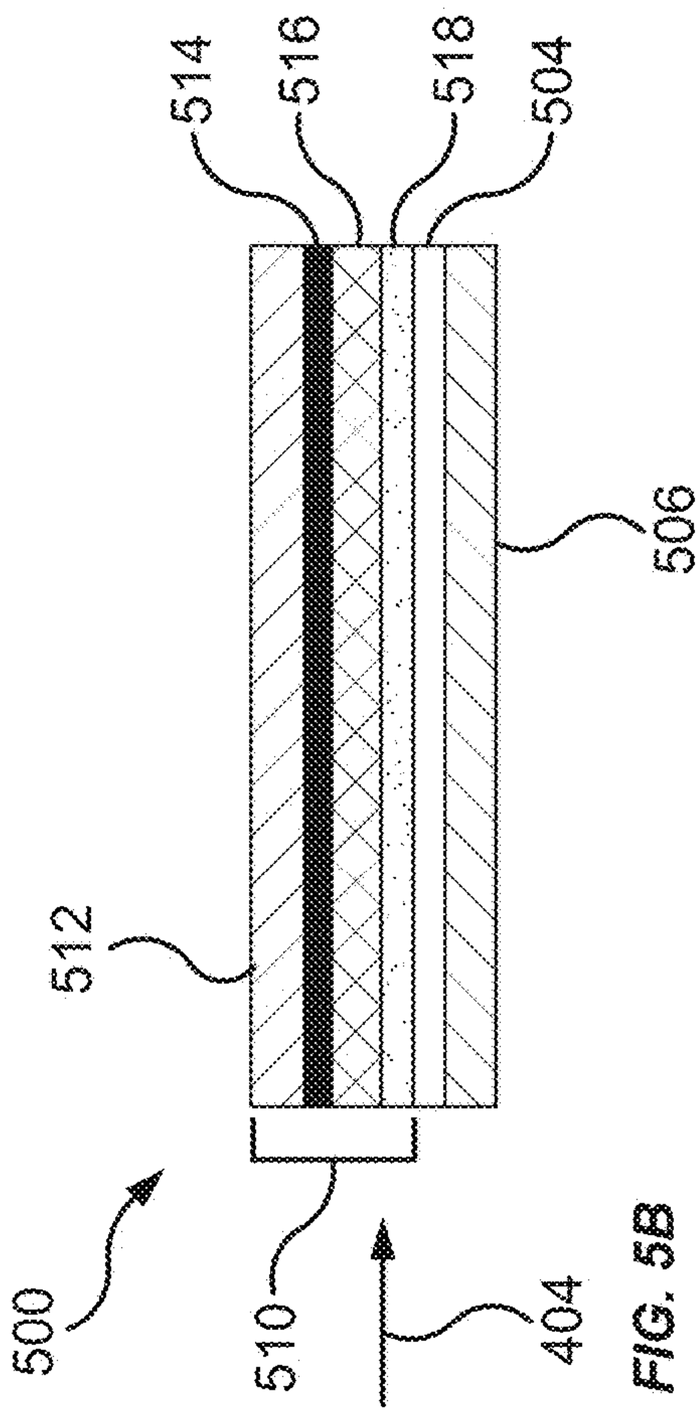


FIG. 5B

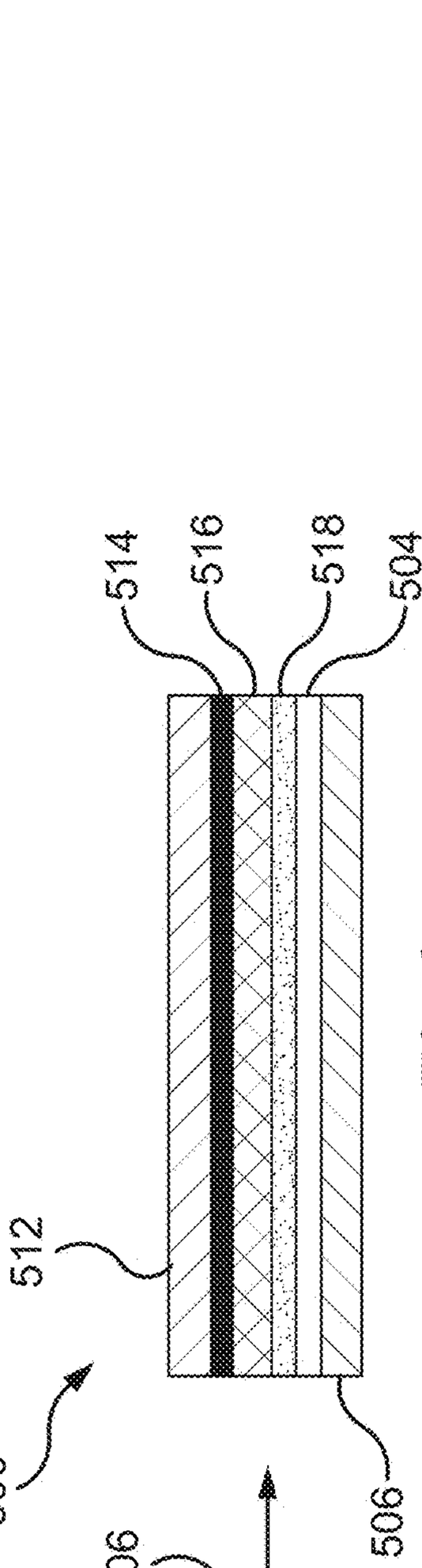
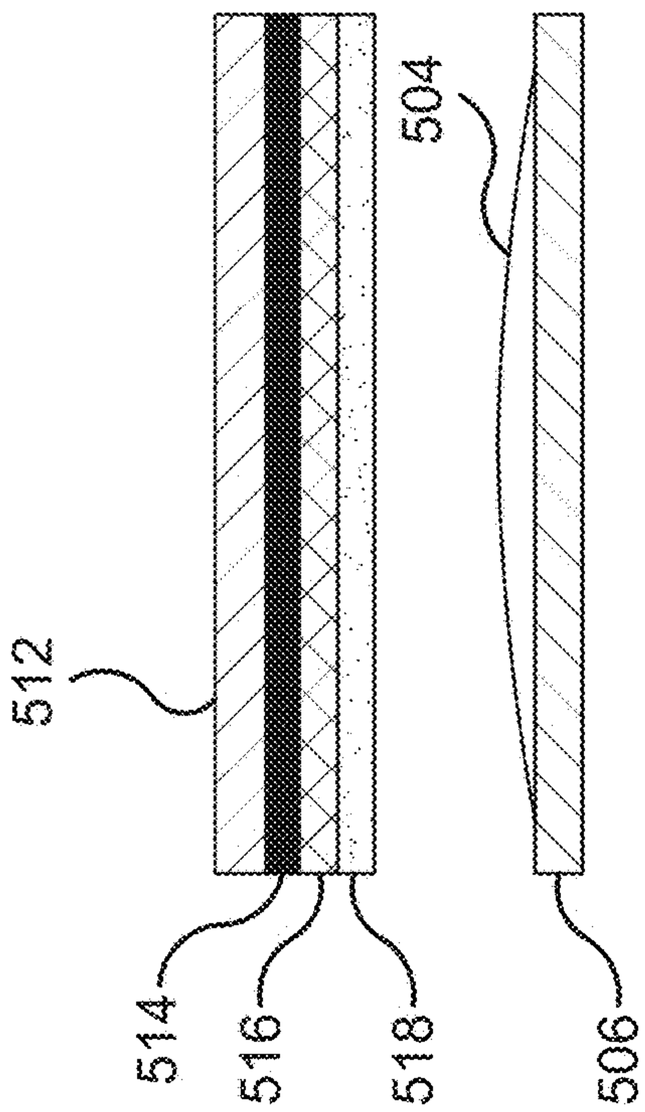


FIG. 5C



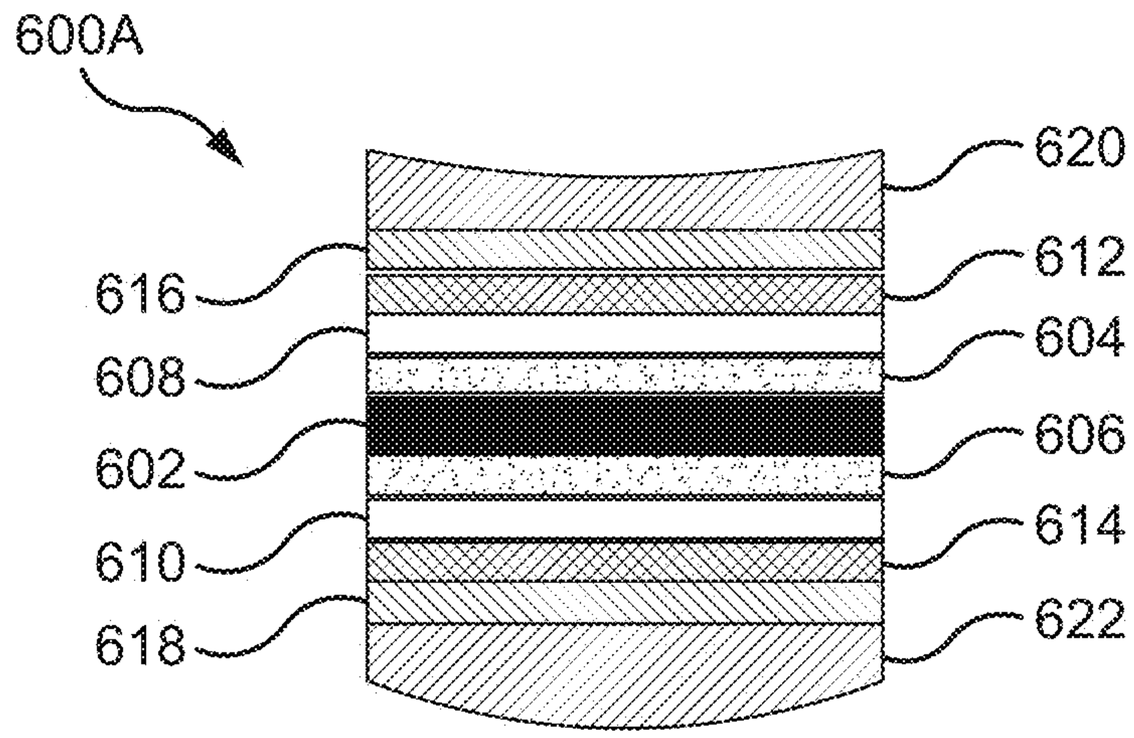


FIG. 6A

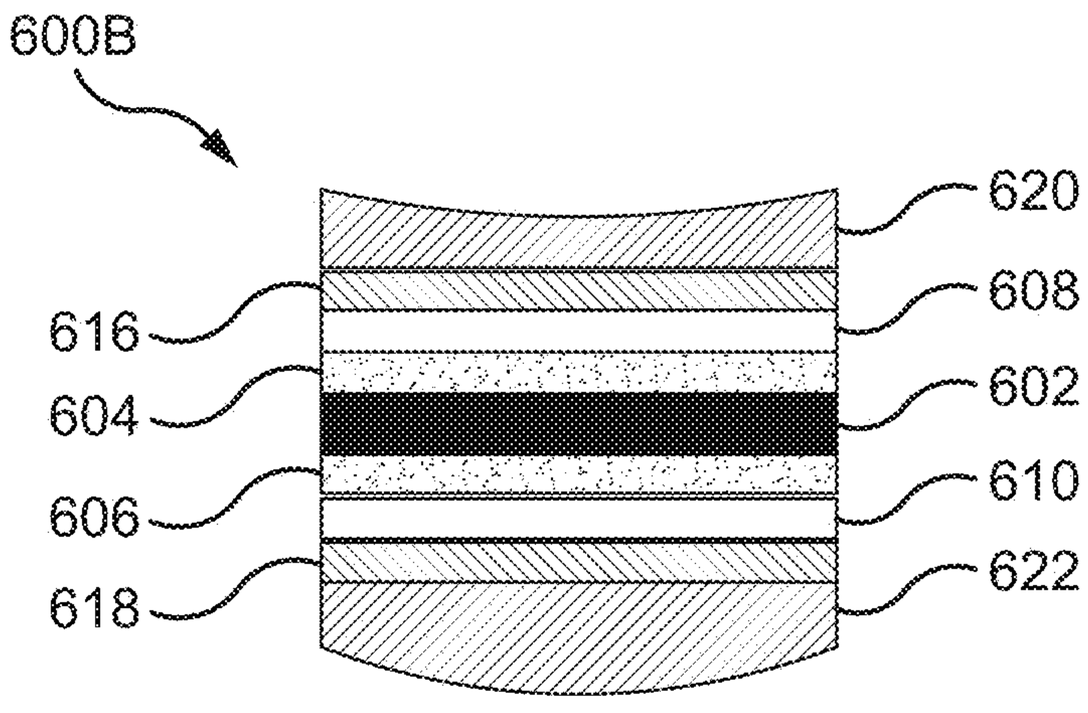


FIG. 6B

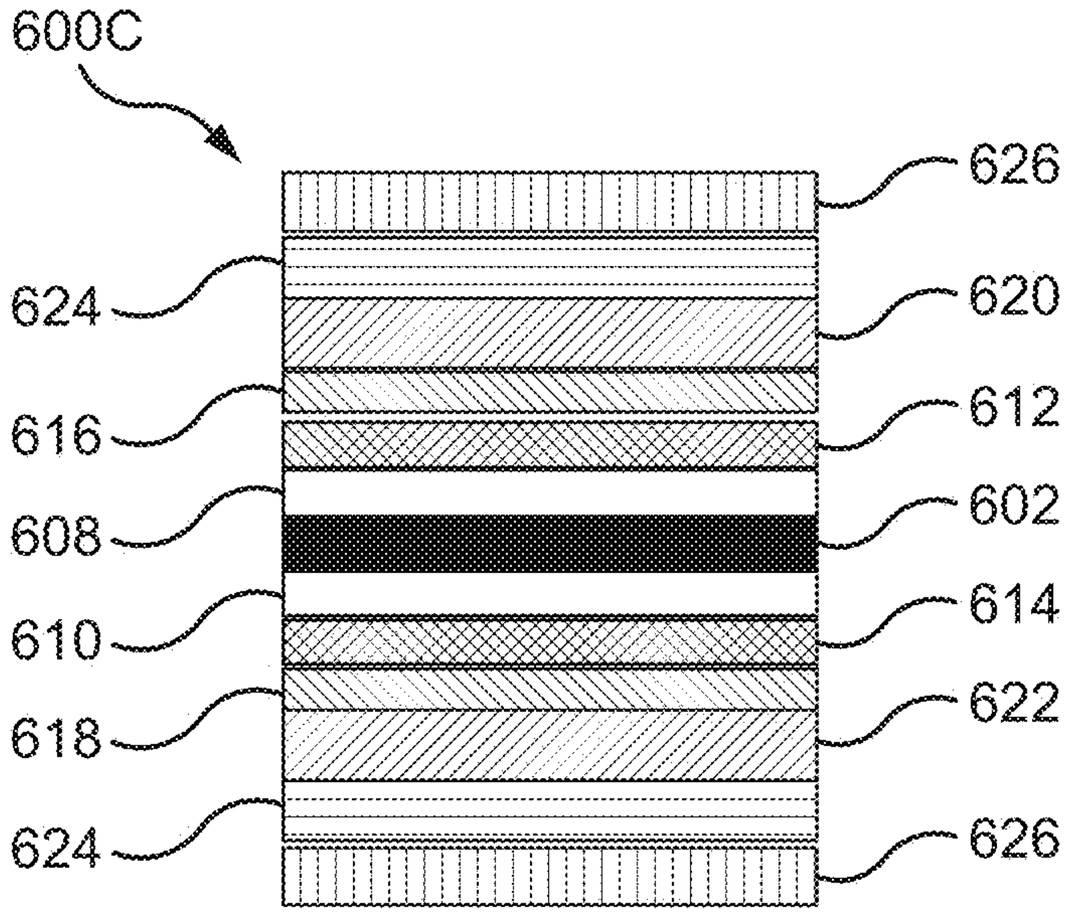


FIG. 6C

DIRECT BONDING USING LOW INDEX FILM AND LAMINATION FOR WAVEGUIDE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Ser. No. 63/636,979, filed Apr. 22, 2024, which is incorporated by reference herein in its entirety.

BACKGROUND

Field

[0002] Embodiments of the present disclosure generally relate to waveguide combiners. More specifically, embodiments described herein provide for methods of forming waveguide combiners.

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 three-dimensionally generated 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. Image sharpness of the virtual image may be affected by the environment.

[0005] One challenge is displaying a virtual image overlaid on an ambient environment. Waveguide combiners, such as augmented reality waveguide combiners, are used to assist in overlaying images. Generated light is propagated through a waveguide combiner until the light exits the waveguide combiner and is overlaid on the ambient environment. To do so, the generated light needs to undergo total internal reflection (TIR). Waveguide combiners may use a low index film to promote TIR within the waveguide combiner. However, these low index films may be porous and susceptible to alteration by the material of other layers that contact the low index films, impacting the overall performance of the waveguide combiner.

[0006] Accordingly, there is a need for improvements to augmented reality technology.

SUMMARY

[0007] Embodiments of the present disclosure generally relate to waveguide combiners. More specifically, the present disclosure relates to methods of forming waveguide combiners.

[0008] In an embodiment, a waveguide is provided. The waveguide includes a waveguide stack including a waveguide substrate having a top surface and a bottom surface, a first low index layer disposed on the top surface, a first cap layer disposed on the first low index layer, a first lens disposed on the first cap layer, and a first optically clear adhesive layer between the first low index layer and the first lens.

[0009] In another embodiment, a waveguide is provided. The waveguide includes a waveguide stack including a waveguide substrate having a top surface and a bottom surface, a first low index layer disposed on the top sur face, a first cap layer disposed on the first low index layer, a first lens disposed on the first cap layer, and a first optically clear adhesive layer between the first low index layer and the first lens. The waveguide stack further includes a first anti-reflective coating layer between a top surface of a waveguide substrate and the first low index layer.

[0010] In yet another embodiment, a method of forming a waveguide is provided. The method includes dispensing a liquid optically clear adhesive layer on a lens, placing a waveguide stack including a first low index layer onto the liquid optically clear adhesive opposite the lens, and curing the liquid optically clear adhesive. The waveguide stack further includes a first cap layer disposed on the first low index layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] 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 of the present disclosure and are therefore not to be considered limiting of scope, and the present disclosure may admit to other equally effective embodiments.

[0012] FIG. **1** is a front view of a waveguide, according to certain embodiments.

[0013] FIG. **2** illustrates a flow chart of a method for forming a waveguide, according to certain embodiments.

[0014] FIGS. **3**A-**3**D illustrate a waveguide substrate undergoing the method of FIG. **2**, according to certain embodiments.

[0015] FIG. **4** illustrates a flow chart of a method for forming a waveguide, according to certain embodiments.

[0016] FIGS. **5**A-**5**C illustrate a waveguide substrate undergoing the method of FIG. **4**, according to certain embodiments.

[0017] FIG. **6**A illustrates a schematic, cross-sectional view of a waveguide, according to certain embodiments.

[0018] FIG. **6**B illustrates a schematic, cross-sectional view of a waveguide, according to certain embodiments.

[0019] FIG. **6**C illustrates a schematic, cross-sectional view of a waveguide, according to certain embodiments.

[0020] 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

[0021] Embodiments of the present disclosure generally relate to waveguide combiners. More specifically, the present disclosure relates to methods of forming waveguide combiners.

[0022] Waveguide combiners, used for augmented reality, may include a lens disposed on the outside surfaces for various purposes, such as to protect the waveguide combiner or as part of a prescription. The lens may be attached to the waveguide combiner using an adhesive around the edge of waveguide. This method, however, creates an air gap between waveguide and lens. Due to the low index of air, light is trapped inside the waveguide and propagates to a predetermined location. However, the air gap impacts the reliability of assembled lens.

[0023] Alternatively, direct bonding may be used to secure the lens to the waveguide combiner by using an adhesive layer that can improve the reliability of the assembly. This bonding method presents an issue for waveguide combiners that rely on total internal reflection (TIR). To function, these waveguide combiners require a difference of refractive index between the two materials at the interface of the waveguide combiner and the adhesive layer. A low index film may be used between the waveguide combiner and the adhesive to promote functionality of the waveguide combiner. The low index film should have a refractive index close to air, as this is ideal for TIR and important for the field of view of the waveguide combiner. The low index film should be thick enough to isolate any evanescent loss from waveguide to outside media, such as to the adhesive layer. However, a majority of low index films are made of porous films, which are not mechanically robust or liquid proof. When these porous low index films contact the adhesive layer, the adhesive material penetrates into the low index film, due to porosity of the low index film, and alters the performance of the low index film, affecting TIR within the waveguide combiner and impacting the overall performance of the device.

[0024] The present disclosure provides a method to laminate a low index coating to a lens, such as a cover lens or a prescription lens, including the choice of adhesive, the lamination process, and the manufacturing process to improve low index coating reliability and compatibility with adhesives. Additionally, the present disclosure provides a waveguide having a cap layer disposed between the waveguide and at least one lens.

[0025] FIG. **1** is a front view of a waveguide **100**, according to certain embodiments. It is to be understood that the waveguide **100** described herein is an exemplary waveguide and that other waveguides may be used with or modified to accomplish aspects of the present disclosure. The waveguide **100** includes a plurality of structures **102**. The structures **102** may be disposed over, under, or on a surface **103** of a substrate **101**, or disposed in the substrate **101**. The structures **102** are nanostructures having a sub-micron critical dimension, e.g., a width less than **1** micrometer. Regions of the structures **102** correspond to one or more gratings **104**. In one embodiment, which can be combined with other embodiments described herein, the waveguide **100** includes at least a first grating **104***a* corresponding to an input coupling grating and a third grating **104***c* corresponding to an output coupling grating. In another embodiment, which can be combined with other embodiments described herein, the waveguide **100** further includes a second grating **104***b*. The second grating **104***b* corresponds to a pupil expansion grating or a fold grating.

[0026] FIG. **2** illustrates a flow chart of a method **200** for forming a waveguide, according to certain embodiments. FIGS. **3**A-**3**E illustrate a waveguide **300** undergoing the method of FIG. **2**, according to certain embodiments.

[0027] The method **200** begins with either operation **202**A or operation **202**B. In operation **202**A of method **200**, a waveguide stack **320** is laminated with a first optically clear adhesive layer **302**. The waveguide stack **320** includes a waveguide substrate **322**, an anti-reflective coating layer **324**, a low index layer **326**, and a cap layer **328**. The waveguide substrate **322** may be a diffractive waveguide that includes surface relief gratings, e.g., one or more gratings **104**. The waveguide substrate **322** as a diffractive waveguide may be made of high index materials, such as high-index glass having a refractive index of about 1.7 to about 2.4, lithium niobate, silicon carbide (SiC), or Indium tin oxide (ITO). The waveguide substrate **322** may also include high index optical coatings deposited on the surface of the waveguide substrate **322**, such as titanium oxide (TiO), niobium oxide (NbO), silicon nitride (SiN), tantalum oxide (TaO), silicon carbide (SiC), or a combination thereof.

[0028] Alternatively, the waveguide substrate **322** may be a reflective waveguide having reflection layers embedded within the waveguide substrate **322**. The anti-reflective coating layer **324** is a coating with a thickness that decreases the reflectivity of the waveguide substrate **322** and may be made of anti-reflective materials, such as silicon dioxide (SiO_2), silicon nitrile (SiN), silicon oxynitride (SiON), titanium dioxide (TiO_2), niobium oxide (NbO), aluminum oxide (AlO), zirconium oxide (ZrO) or a combination thereof. For example, the anti-reflective coating layer **324** may include alternating layers of SiO_2 and TiO_2 or a single layer of SiO_2 having a thickness of about 100 nm. The low index layer **326** is made of porous materials having a refractive index of about 1.0 to about 1.4, such as porous silica or fluorinated polymers. For example, the low index layer **326** may be a porous silica layer having a refractive index of about 1.05 to about 1.25.

[0029] The cap layer **328** is a layer of a low index film and seals the porosity of the low index layer **326** from a subsequent adhesive layer such that the adhesive or other material does not leak into the porous film. The cap layer **328** then preserves the porosity and refractive index of the low index layer **326**, ensuring consistent performance of the waveguide **300**. The cap layer **328** may be made of suitable materials, such as silicon oxide (SiO), aluminum oxide (AlO), low density SiO made from the formation of an inorganic colloidal suspension and gelation of the suspension in a continuous liquid phase, or an organic coating. It can be deposited by spin coating, PVD, CVD or ALD. The film thickness of this cap layer is tuned to function as anti-reflective coating as well.

[0030] For lamination, a first liner (not shown) opposite the second liner **304** of the first optically clear adhesive layer **302** is removed, exposing a surface of the first optically clear adhesive layer **302**. The exposed surface of the first optically clear adhesive layer **302** is then pressed onto or otherwise makes physical contact with the waveguide stack **320**. After lamination, the first optically clear adhesive layer **302** is disposed on the cap layer **328** of the waveguide stack **320**, as shown in FIG. **3**A. Alternatively, the first optically clear adhesive layer **302** may be disposed on the low index layer **326** or any other layer of the waveguide stack **320**. The first optically clear adhesive layer **302** includes a second liner **304** disposed opposite the waveguide stack **320**. The first optically clear adhesive layer **302** may be made of any

optically clear adhesive materials, such as acrylic-based adhesives or silicon-based adhesives.

[0031] Alternatively, in operation **202**B, a lens **330** is laminated with the first optically clear adhesive layer **302** as shown in FIG. **3**B following a lamination process similar to the lamination process in the operation **202**A. The first optically clear adhesive layer **302** includes the second liner **304** disposed opposite the lens **330**. The lens **330** may include prescription lens materials, such as urethane-based polymers, polycarbonates, or thiourethane resins, having a refractive index of about 1.45 to about 1.75, such as about 1.5 to about 1.7, and an abbe number of about 25 to about 65, such as about 31 to about 60. The lens **330** may also be a cover lens made of materials configured to protect the waveguide stack **320**, such as polycarbonates, ultra-thin glass, aluminosilicate glass, or high ion-exchange aluminosilicate glass.

[0032] In operation **204**, the second liner **304** is removed, depending on whether operation **202**A or operation **202**B occurred, and the waveguide stack **320** is laminated or otherwise placed onto the lens **330** as shown in FIG. **3**C. When the waveguide stack **320** is laminated onto the lens **330**, the first optically clear adhesive layer **302** or the second optically clear adhesive layer **312** contact the lens **330** or the waveguide stack **320**, respectively. Optionally, the first optically clear adhesive layer **302**, the second optically clear adhesive layer **312**, or both may be cured in operation **206**. Depending on the materials used for the first optically clear adhesive layer **302** or the second optically clear adhesive layer **312**, curing, such as UV curing, may be required to solidify the first optically clear adhesive layer **302** and the second optically clear adhesive layer **312** to properly bond the waveguide stack **320** to the lens **330**.

[0033] Optionally, the waveguide stack **320** and the lens **330** may be diced in operation **208** into a first section **320**A and a second section **320**B as shown in FIG. **3**D. In some instances, the first optically clear adhesive layer **302** and the second optically clear adhesive layer **312**, the waveguide stack **320**, the lens **330** can be different size from each other. For example, the first optically clear adhesive layer **302** and the second optically clear adhesive layer **312** or the lens **330** can be a web-like sheet, the waveguide stack **320** can be a substrate, the lens **330** can be an injection-molded die-level part. For these scenarios, dicing processes (such as laser dicing) are completed at certain steps to facilitate the method **200** and create final parts. This laser dicing can be used for each layer, or can be used for laminated two layers or three layers. For example, laser dicing or die-cutting can be used to trim the first optically clear adhesive layer **302** and the second optically clear adhesive layer **312** to desired shape after operation **202** or operation **204**. Laser dicing can be used to dice the laminated layers into die-shape as final parts.

[0034] FIG. **4** illustrates a flow chart of a method **400** for forming a waveguide, according to certain embodiments. FIGS. **5**A-**5**C illustrate a waveguide **500** undergoing the method of FIG. **4**, according to certain embodiments.

[0035] In operation **402** of method **400**, a liquid optically clear adhesive dispenser **502** is used to dispense or otherwise deposit a liquid optically clear adhesive **504** on a surface of a lens **506**, as shown in FIG. **5**A. The liquid optically clear adhesive **504** is an optically clear resin or optically clear adhesive that is in a liquid form. The liquid optically clear adhesive **504** penetrates into the pores of the layer beneath it. As such, in embodiments using the liquid optically clear adhesive dispenser **502** and the liquid optically clear adhesive **504**, a cap layer **518** is required to be disposed between the liquid optically clear adhesive **504** and a low index layer **516** of a waveguide stack **510** to prevent the liquid optically clear adhesive **504** from penetrating and, ultimately, altering the performance of the low index layer **516** as shown in FIG. **5**B. The lens **506** is shown to be flat or substantially flat. Alternatively, the lens **506** may be concave, convex, or a combination thereof. The lens **506** may be a prescription lens having materials, such as urethane-based polymers, polycarbonates, or thiourethane resins, having a refractive index of about 1.45 to about 1.75, such as about 1.5 to about 1.7, and an abbe number of about 25 to about 65, such as about 31 to about 60. The lens **506** may also be a cover lens made of materials configured to protect the waveguide stack **510**, such as polycarbonates, ultra-thin glass, aluminosilicate glass, or high ion-exchange aluminosilicate glass. In embodiments where the lens **506** is a cover lens, the thickness of the lens may be about 0.2 um to about 2 mm and depends on the material used for the cover lens. For example, if a polycarbonate is used, the thickness may be about 50 μm to about 2 mm.

[0036] In operation **404**, the waveguide stack **510** is placed on the liquid optically clear adhesive **504** opposite the lens **506** as shown in FIG. **5**B. The waveguide stack **510** includes a waveguide substrate **512**, an anti-reflective coating layer **514**, the low index layer **516**, and the cap layer **518**. The waveguide stack **510** may be a diffractive waveguide that includes surface relief gratings, e.g., one or more gratings **104**. The waveguide stack **510** as a diffractive waveguide may be made of high index materials, such as high-index glass having a refractive index of about 1.7 to about 2.4, lithium niobate, silicon carbide (SiC), or Indium tin oxide (ITO). The waveguide stack **510** may also include high index optical coatings deposited on the surface of the waveguide stack **510**, such as titanium oxide (TiO), niobium oxide (NbO), silicon nitride (SiN), tantalum oxide (TaO), silicon carbide (SiC), or a combination thereof. Alternatively, the waveguide stack **510** may be a reflective waveguide having reflection layers embedded within the waveguide stack **510**. The anti-reflective coating layer **514** is a coating with a thickness that decreases the reflectivity of the waveguide stack **510** and may be made of anti-reflective materials, such as silicon dioxide (SiO_2), silicon nitrile (SiN), silicon oxynitride (SiON), titanium dioxide (TiO_2), niobium oxide (NbO), aluminum oxide (AlO), zirconium oxide (ZrO), or a combination thereof. For example, the anti-reflective coating layer **514** may include alternating layers of SiO_2 and TiO_2 or a single layer of SiO_2 having a thickness of about 100 nm. The low index layer **516** is made of porous materials having a refractive index of about 1.0 and about 1.4, such as porous silica or fluorinated polymers. For example, the low index layer **516** may be a porous silica layer having a refractive index of about 1.10 to about 1.2. The cap layer **518** is a layer of a low index film and seals the porosity of the low index layer **516** from a subsequent adhesive layer such that the adhesive or other material does not leak into the porous film. The cap layer **518** then preserves the porosity and refractive index of the low index layer **516**, ensuring consistent performance of the waveguide **300**. The cap layer **518** may be made of suitable materials, such as silicon oxide (SiO), aluminum oxide (AlO), or an organic coating.

[0037] In operation **406**, the liquid optically clear adhesive **504** is cured, such as by UV curing, to solidify the liquid optically clear adhesive **504** into an optically clear adhesive layer binding the waveguide stack **510** to the lens **506** as shown in FIG. **5**C. In optional operation **408**, the waveguide stack **510**, the liquid optically clear adhesive **504**, the lens **506**, or a combination thereof may be diced similar to operation **208** of method **200**, described above.

[0038] FIG. **6**A illustrates a schematic, cross-sectional view of a waveguide stack **600**A, according to certain embodiments. The waveguide stack **600**A may be formed using either the method **200**, the method **400**, or a combination thereof.

[0039] As shown in FIG. **6**A, the waveguide stack **600**A includes a waveguide substrate **602** with a first anti-reflective coating layer **604** disposed on one side and a second anti-reflective coating layer **606** disposed on an opposing side. The first anti-reflective coating layer **604** has a first low index layer **608** disposed thereon. Similarly, the second anti-reflective coating layer **606** has a second low index layer **610** disposed thereon. The layer stack continues with a first cap layer **612** disposed on the first low index layer **608** and a second cap layer **614** disposed on the second low index layer **610**. A first lens **620** is coupled to or bound to the first cap layer **612** by a first optically clear adhesive layer **616**. The first lens **620** may be bound using either the method **200**, the method **400**, or a combination thereof. Similarly, a second lens **622** is coupled or bound to the second cap layer **614** by a second optically clear adhesive layer **618**. The first lens **620** and the second lens **622** are shown to be concave and convex, respectively. Alternatively, the first lens **620** and the second lens **622** may be flat or substantially flat. The first lens **620**, the second lens **622**, or both may be prescription lenses having materials, such as urethane-based polymers, polycarbonates, or thiourethane resins, having a refractive index of about 1.45 to about 1.75, such as about 1.5 to about 1.7, and an abbe number of about 25 to about 65, such as about 31 to about 60. The first lens **620**, the second lens **622**, or both may also be a cover lens made of materials configured to protect the waveguide stack **320**, such as polycarbonates, ultra-thin glass, aluminosilicate glass, or high ion-exchange aluminosilicate glass. In embodiments where the first lens **620**, the second lens **622**, or both are cover lenses, the thickness of each respective lens may be about 0.2 μm to about 2 mm and depends on the material used for the cover lens. For example, if a polycarbonate is used, the thickness may be about 50 μm to about 2 mm.

[0040] FIG. **6**B illustrates a schematic, cross-sectional view of a waveguide stack **600**B, according to certain embodiments. The waveguide stack **600**A may be formed using either the method **200**, the method **400**, or a combination thereof.

[0041] As shown in FIG. **6**B, the waveguide stack **600**B includes a layer stack without the first cap layer **612** or the second cap layer **614**. For example, the waveguide stack **600**B includes the waveguide substrate **602**, the first anti-reflective coating layer **604** and the second anti-reflective coating layer **606** disposed on either side of the waveguide substrate **602**, the first low index layer **608** disposed on the first anti-reflective coating layer **604**, and the second low index layer **610** disposed on the second anti-reflective coating layer **606**. In this embodiment, the first lens **620** is coupled or bound to the first low index layer **608** directly by the first optically clear adhesive layer **616** and the second lens **622** is coupled or bound to the second low index layer **610** directly by the second optically clear adhesive layer **618**. The first lens **620** and the second lens **622** are shown to be concave and convex, respectively. Alternatively, the first lens **620** and the second lens **622** are shown to be flat or substantially flat. The first lens **620**, the second lens **622**, or both may be prescription lenses having materials, such as urethane-based polymers, polycarbonates, or thiourethane resins, having a refractive index of about 1.45 to about 1.75, such as about 1.5 to about 1.7, and an abbe number of about 25 to about 65, such as about 31 to about 60. The first lens **620**, the second lens **622**, or both may also be a cover lens made of materials configured to protect the waveguide stack **320**, such as polycarbonates, ultra-thin glass, aluminosilicate glass, or high ion-exchange aluminosilicate glass. In embodiments where the first lens **620**, the second lens **622**, or both are cover lenses, the thickness of each respective lens may be about 0.2 μm to about 2 mm and depends on the material used for the cover lens. For example, if a polycarbonate is used, the thickness may be about 50 μm to about 2 mm.

[0042] FIG. **6**C illustrates a schematic, cross-sectional view of a waveguide stack **600**C, according to certain embodiments. The waveguide stack **600**A may be formed using either the method **200**, the method **400**, or a combination thereof.

[0043] As shown in FIG. **6**C, the waveguide stack **600**C includes a layer stack similar to the layer stack of the waveguide stack **600**A shown in FIG. **6**A. The waveguide stack **600**C includes the waveguide substrate **602**, the first anti-reflective coating layer **604** and the second anti-reflective coating layer **606** disposed on either side of the waveguide substrate **602**, the first low index layer **608** disposed on the first anti-reflective coating layer **604**, the second low index layer **610** disposed on the second anti-reflective coating layer **606**, the first cap layer **612** disposed on the first low index layer **608**, and the second cap layer **614** disposed on the second low index layer **610**. The first lens **620** is coupled or bound to the first cap layer **612** by the first optically clear adhesive layer **616** and the second lens **622** is coupled or bound to the second cap layer **614** by the second optically clear adhesive layer **618**. In this embodiment, the first lens **620** and the second lens **622** are flat or substantially flat. Alternatively, the first lens **620**, the second lens **622**, or both may be concave, convex, or a combination thereof. The first lens **620**, the second lens **622**, or both may be prescription lenses having materials, such as urethane-based polymers, polycarbonates, or thiourethane resins, having a refractive index of about 1.45 to about 1.75, such as about 1.5 to about 1.7, and an abbe number of about 25 to about 65, such as about 31 to about 60. The first lens **620**, the second lens **622**, or both may also be a cover lens made of materials configured to protect the waveguide stack **320**, such as polycarbonates, ultra-thin glass, aluminosilicate glass, or high ion-exchange aluminosilicate glass. In embodiments where the first lens **620**, the second lens **622**, or both are cover lenses, the thickness of each respective lens may be about 0.2 μm to about 2 mm and depends on the material used for the cover lens. For example, if a polycarbonate is used, the thickness may be about 50 μm to about 2 mm.

[0044] The first lens **620**, the second lens **622**, or both may also include one or more protective coatings, e.g., a first protective coating layer **624** and a second protective coating layer **626**, disposed opposite the optically clear adhesive

layer, e.g., the first optically clear adhesive layer **616** or the second optically clear adhesive layer **618**. The first protective coating layer **624**, the second protective coating layer **626**, or both may be protective coatings, such as anti-scratch coatings, anti-glare coatings, anti-reflection coatings, ultraviolet protection coatings, photochromatic coatings, and blue-light reduction coatings. In embodiments where there are more than one protective coating, as shown in FIG. **6**C, the protective coating layers need not be the same, e.g., the first protective coating layer **624** is an anti-reflection coating and the second protective coating layer **626** is an anti-scratch coating.

[0045] The present disclosure provides a waveguide and method of forming a waveguide that includes a cap layer disposed between an adhesive layer and a low index layer over a waveguide substrate. The cap layer prevents adhesive material from the adhesive layer from penetrating the low index layer, preserving the porosity of the low index layer. This allows for consistent, reliable performance of the low index layer in promoting total internal reflection within the waveguide substrate, improving the overall performance of the device.

[0046] When introducing elements of the present disclosure or exemplary aspects or embodiments thereof, the articles "a," "an," "the" and "said" are intended to mean that there are one or more of the elements.

[0047] The terms "comprising," "including" and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0048] The term "coupled" is used herein to refer to the direct or indirect coupling between two objects. For example, if object A physically touches object B and object B touches object C, the objects A and C may still be considered coupled to one another—even if objects A and C do not directly physically touch each other. For instance, a first object may be coupled to a second object even though the first object is never directly in physical contact with the second object.

[0049] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A waveguide, comprising:

a waveguide stack including a waveguide substrate having a top surface and a bottom surface;

a first low index layer disposed on the top surface;

a first cap layer disposed on the first low index layer;

a first lens disposed on the first cap layer; and

a first optically clear adhesive layer between the first low index layer and the first lens.

2. The waveguide of claim **1**, further comprising a first anti-reflective coating layer between the top surface and the first low index layer.

3. The waveguide of claim **1**, wherein the first optically clear adhesive layer is formed by curing a liquid optically clear adhesive.

4. The waveguide of claim **1**, further comprising a protective coating layer disposed on the lens opposite the low index layer.

5. The waveguide of claim **1**, wherein the first low index layer comprises a refractive index of about 1 and about 1.3.

6. The waveguide of claim **1**, wherein the first cap layer is configured to seal a porosity of the first low index layer.

7. The waveguide of claim **1**, further comprising a second low index layer disposed on the bottom surface and a second lens disposed on the second low index layer.

8. A method of forming a waveguide, comprising:

laminating a waveguide stack comprising a first low index layer with a first optically clear adhesive layer; and

laminating the waveguide stack onto a lens using the first optically clear adhesive layer.

9. The method of claim **8**, wherein the waveguide stack further comprises a first anti-reflective coating layer between a top surface of a waveguide substrate and the first low index layer.

10. The method of claim **8**, wherein the waveguide stack further comprises a first cap layer disposed between the first low index layer and the first optically clear adhesive layer.

11. The method of claim **8**, wherein a protective coating layer is disposed on the lens opposite the low index layer.

12. The method of claim **8**, further comprising curing the first optically clear adhesive layer.

13. The method of claim **8**, further comprising dicing the waveguide stack after laminating the waveguide stack onto the lens.

14. The method of claim **8**, wherein the first low index layer comprises a refractive index of about 1 and about 1.3.

15. A method of forming a waveguide, comprising:

dispensing a liquid optically clear adhesive layer on a lens;

placing a waveguide stack comprising a first low index layer onto the liquid optically clear adhesive opposite the lens; and

curing the liquid optically clear adhesive.

16. The method of claim **15**, further comprising dicing the waveguide stack after curing the liquid optically clear adhesive.

17. The method of claim **15**, wherein the waveguide stack further comprises a first anti-reflective coating layer between a top surface of a waveguide substrate and the first low index layer.

18. The method of claim **15**, wherein the waveguide stack further comprises a first cap layer disposed on the first low index layer.

19. The method of claim **15**, wherein a protective coating layer is disposed on the lens opposite the low index layer.

20. The method of claim **15**, wherein the first low index layer comprises a refractive index of about 1 and about 1.3.

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