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Fu et al.

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(54) **METHOD TO IMPROVE DISPLAY EFFICIENCY AND UNIFORMITY OF AR WAVEGUIDE**

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(51) **Int. Cl.**

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F21V 8/00	(2006.01)
G02B 1/115	(2015.01)
G02B 6/42	(2006.01)

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

CPC ***G02B 27/0172*** (2013.01); ***G02B 6/0016*** (2013.01); ***G02B 6/0038*** (2013.01); *G02B 1/115* (2013.01); *G02B 6/4212* (2013.01); *G02B 2027/0112* (2013.01)

(58) **Field of Classification Search**

CPC G03F 7/0005; G03F 7/16; G02B 5/1857; G02B 6/136; G02B 27/0172; G02B 6/0016; G02B 6/0038; G02B 1/115; G02B 6/4212; G02B 2027/0112

See application file for complete search history.

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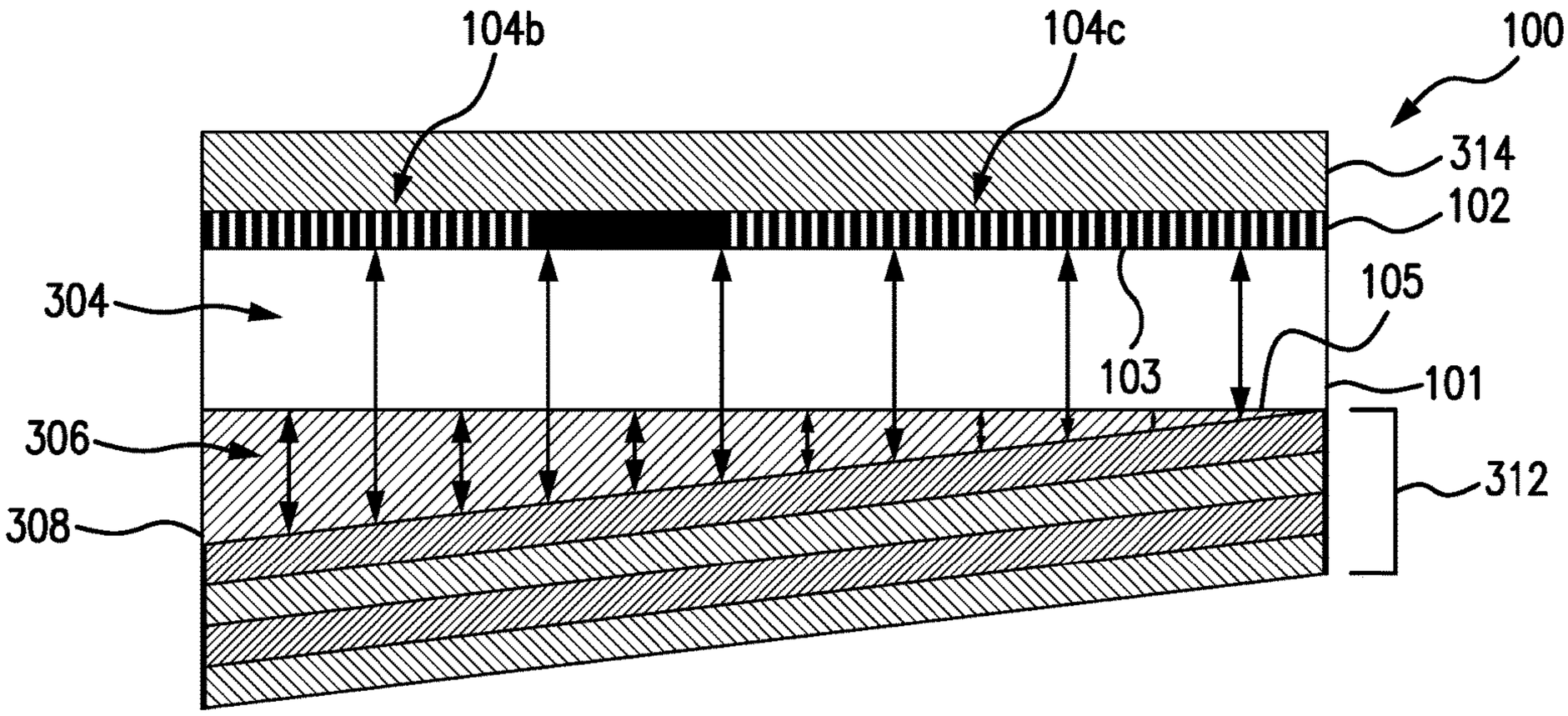
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(57) **ABSTRACT**

Embodiments of the present disclosure generally relate to methods of modifying and engineering the effective thickness of an optical device substrate. The methods provide for depositing a material that is index-matched to the substrate to alter a thickness distribution of the optical device. By adjusting the thickness distribution, the optical path of light is modulated to direct the light to the output coupling grating.

7 Claims, 7 Drawing Sheets



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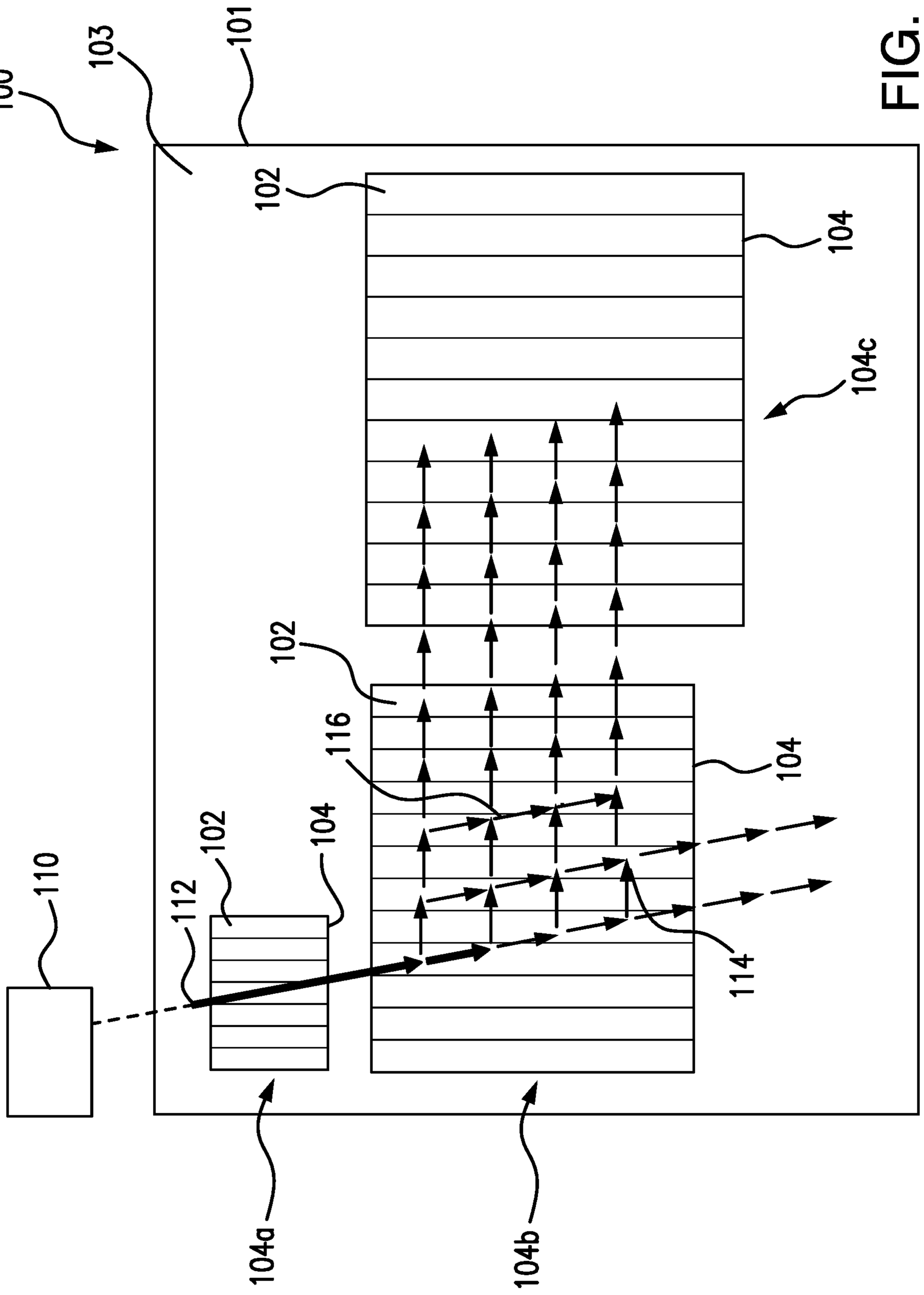
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FIG. 1


100
103
101
102
104
104c
102
116
104
104
102
110
112
114
104a
104b

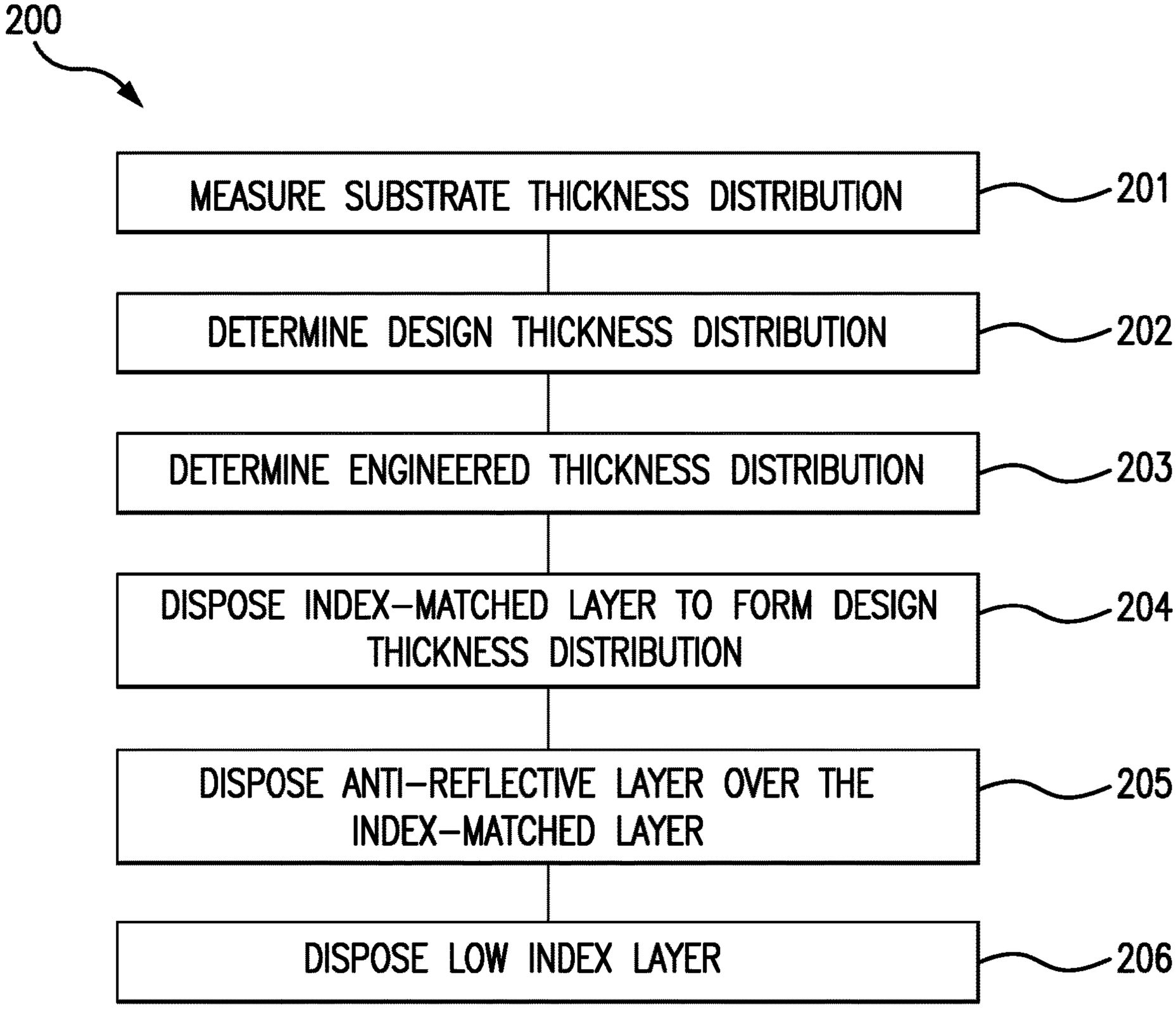

200
MEASURE SUBSTRATE THICKNESS DISTRIBUTION
201
DETERMINE DESIGN THICKNESS DISTRIBUTION
202
DETERMINE ENGINEERED THICKNESS DISTRIBUTION
203
DISPOSE INDEX-MATCHED LAYER TO FORM DESIGN THICKNESS DISTRIBUTION
204
DISPOSE ANTI-REFLECTIVE LAYER OVER THE INDEX-MATCHED LAYER
205
DISPOSE LOW INDEX LAYER
206

FIG. 2

FIG. 3A

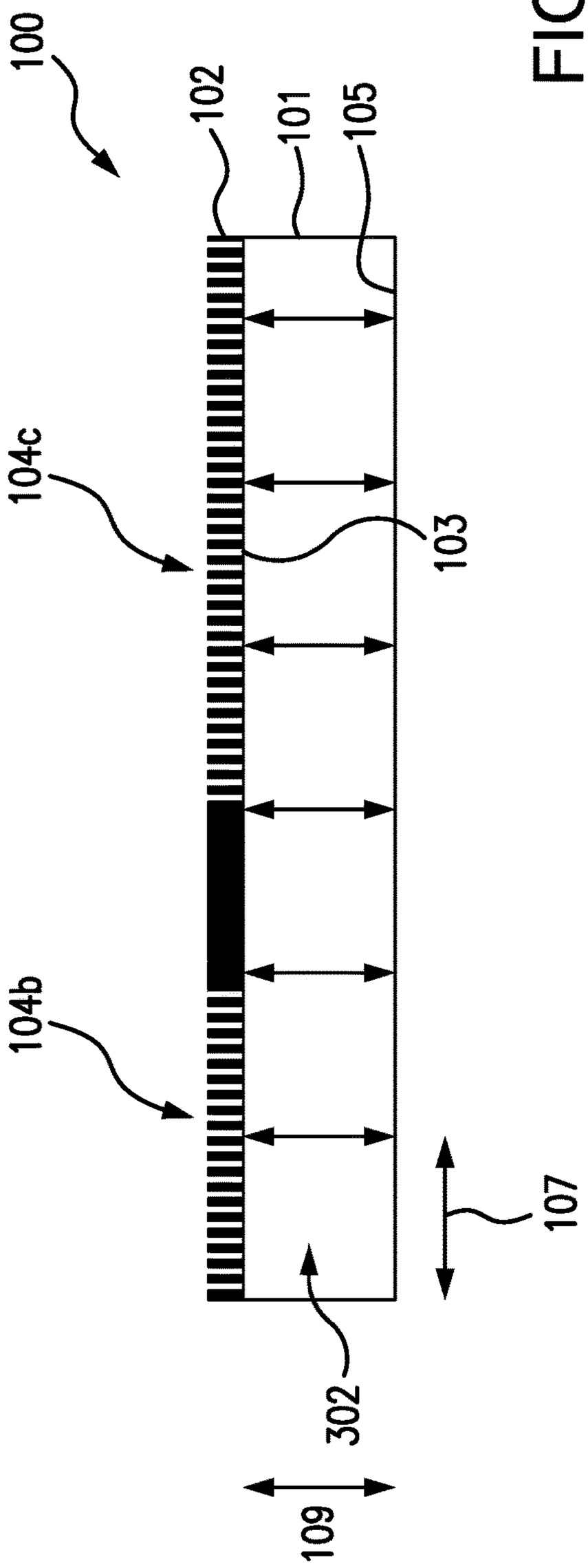
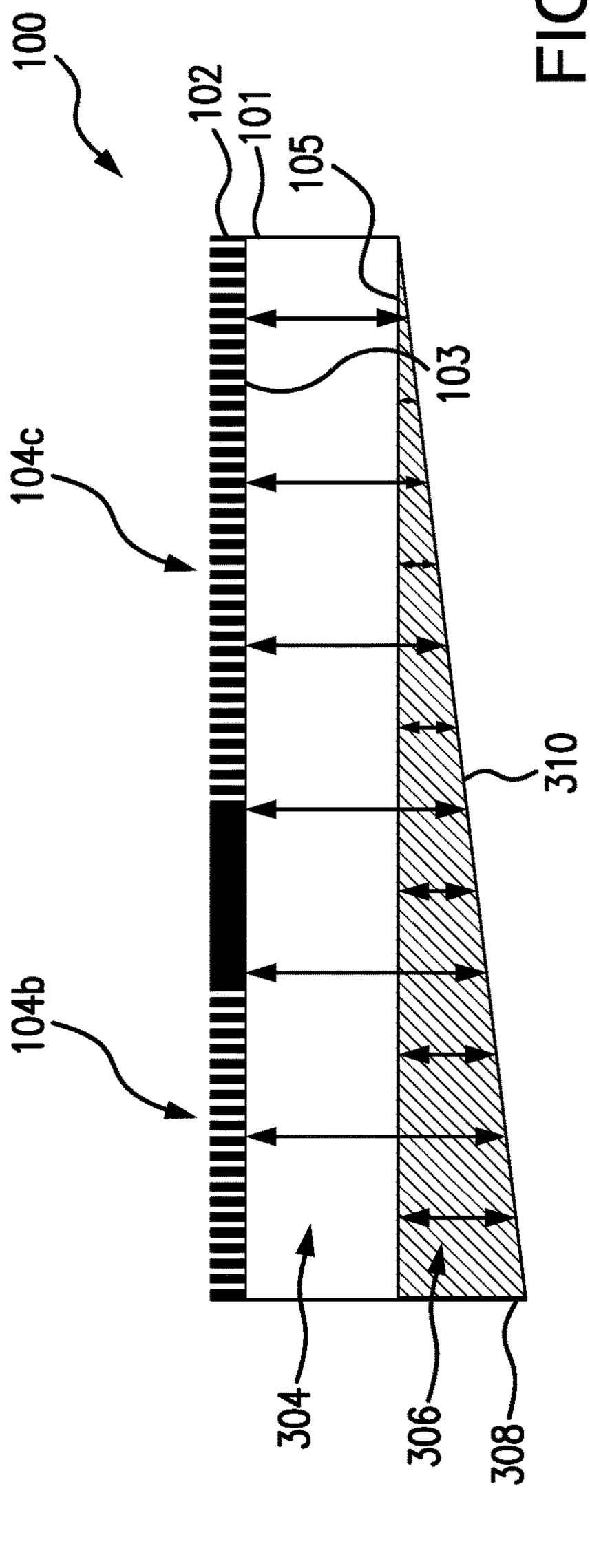

100
102
101
105
104c
103
104b
107
302
109

FIG. 3B


100
102
101
105
104c
103
104b
310
304
306
308

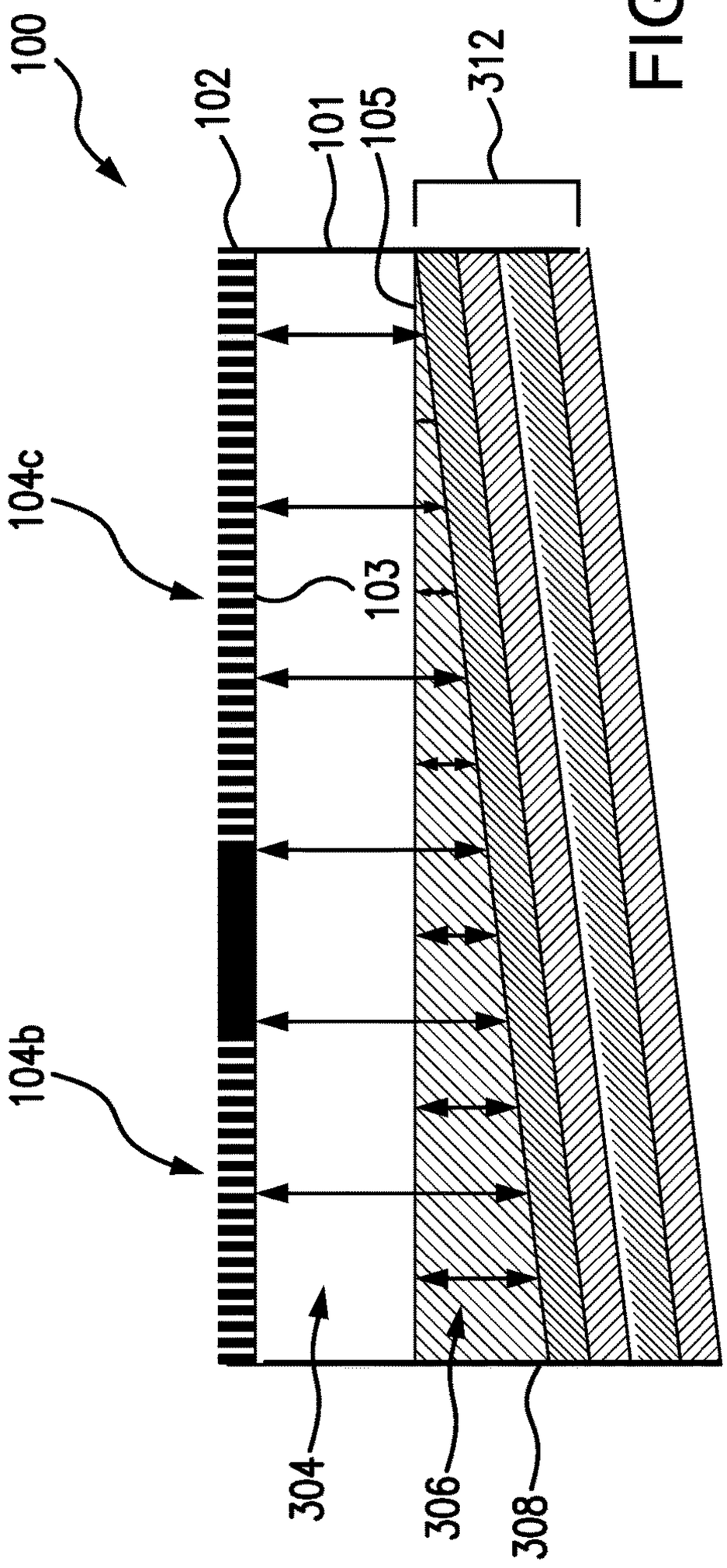

100
102
101
105
312
104c
103
104b
304
306
308

FIG. 3C

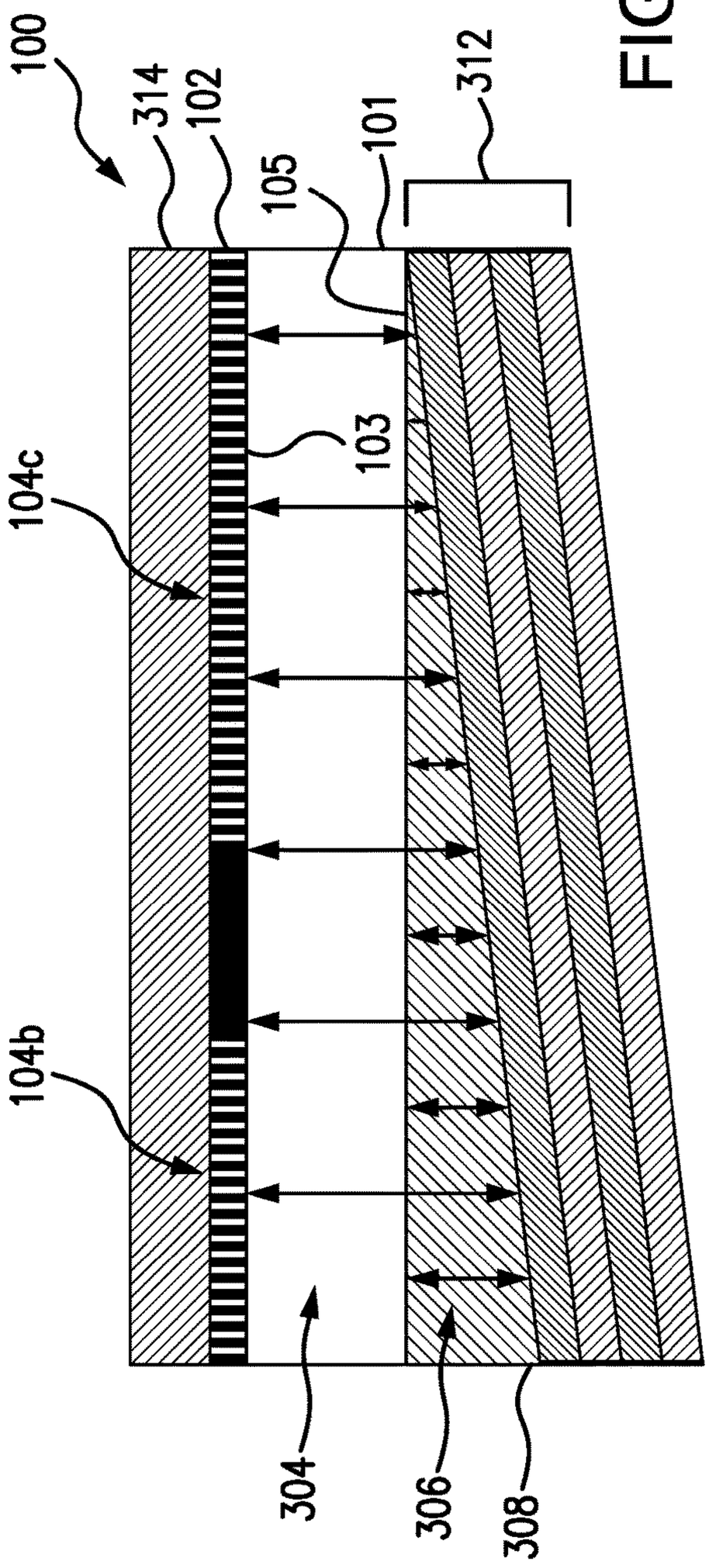

100
314
102
105
101
312
104c
103
104b
304
306
308

FIG. 3D

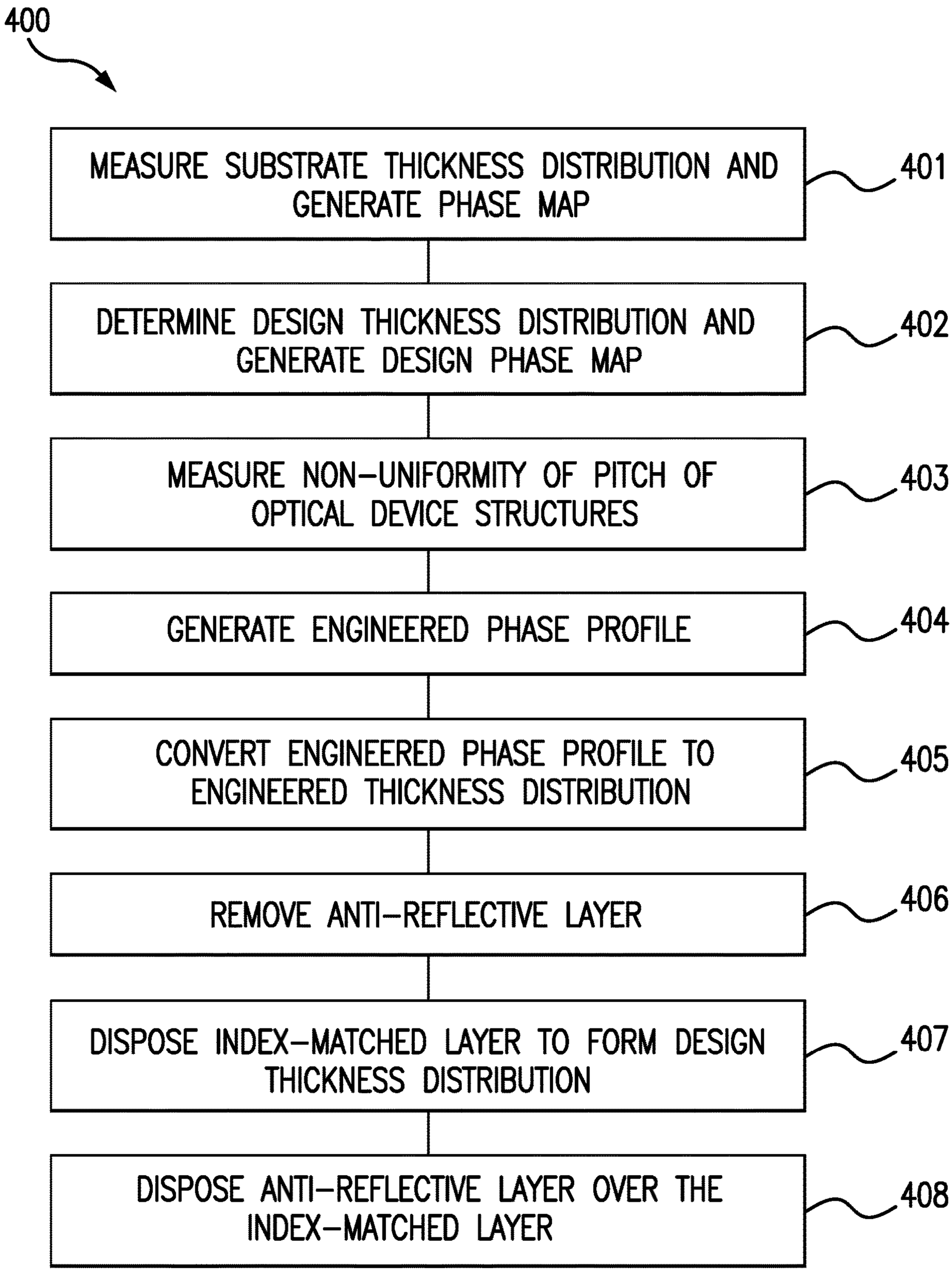

400
MEASURE SUBSTRATE THICKNESS DISTRIBUTION AND GENERATE PHASE MAP
401
DETERMINE DESIGN THICKNESS DISTRIBUTION AND GENERATE DESIGN PHASE MAP
402
MEASURE NON-UNIFORMITY OF PITCH OF OPTICAL DEVICE STRUCTURES
403
GENERATE ENGINEERED PHASE PROFILE
404
CONVERT ENGINEERED PHASE PROFILE TO ENGINEERED THICKNESS DISTRIBUTION
405
REMOVE ANTI-REFLECTIVE LAYER
406
DISPOSE INDEX-MATCHED LAYER TO FORM DESIGN THICKNESS DISTRIBUTION
407
DISPOSE ANTI-REFLECTIVE LAYER OVER THE INDEX-MATCHED LAYER
408

FIG. 4

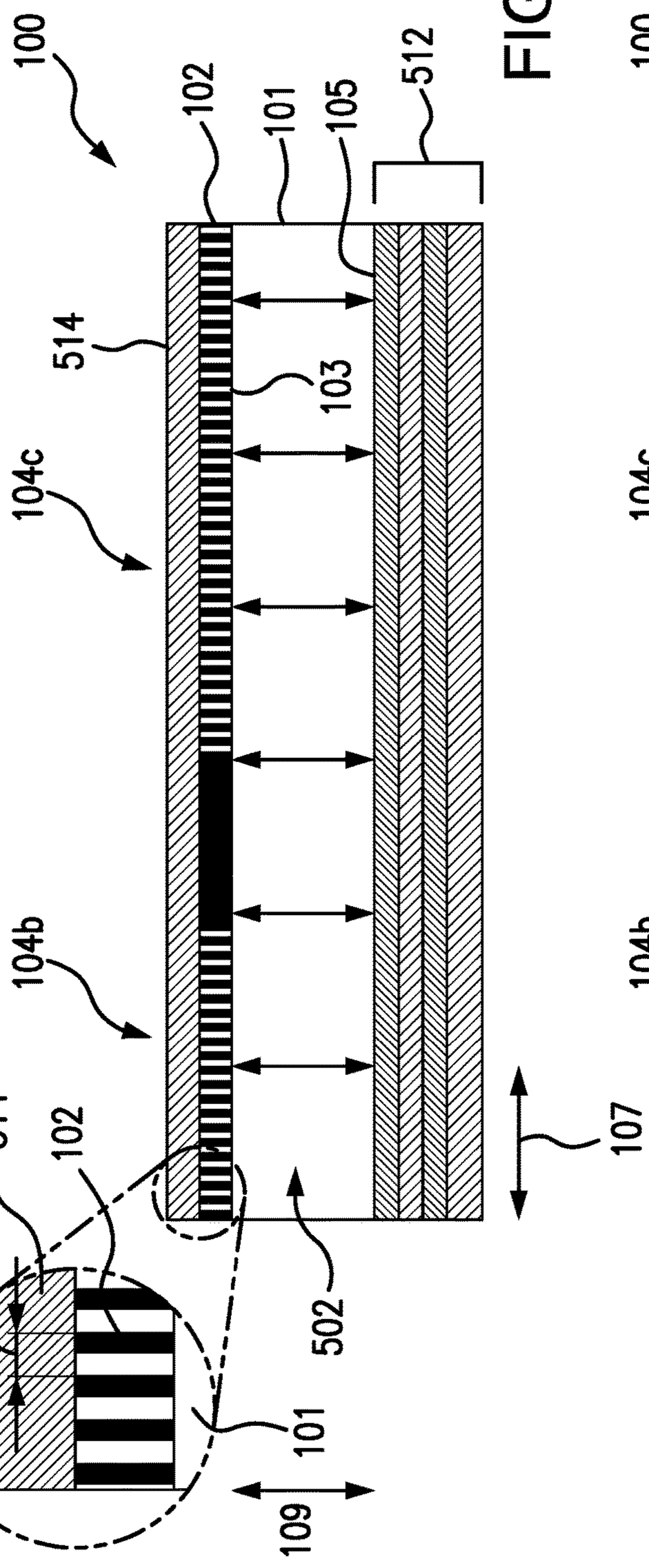

100
102
101
105
512
514
103
104c
104b
107
516
514
102
502
101
109

FIG. 5A

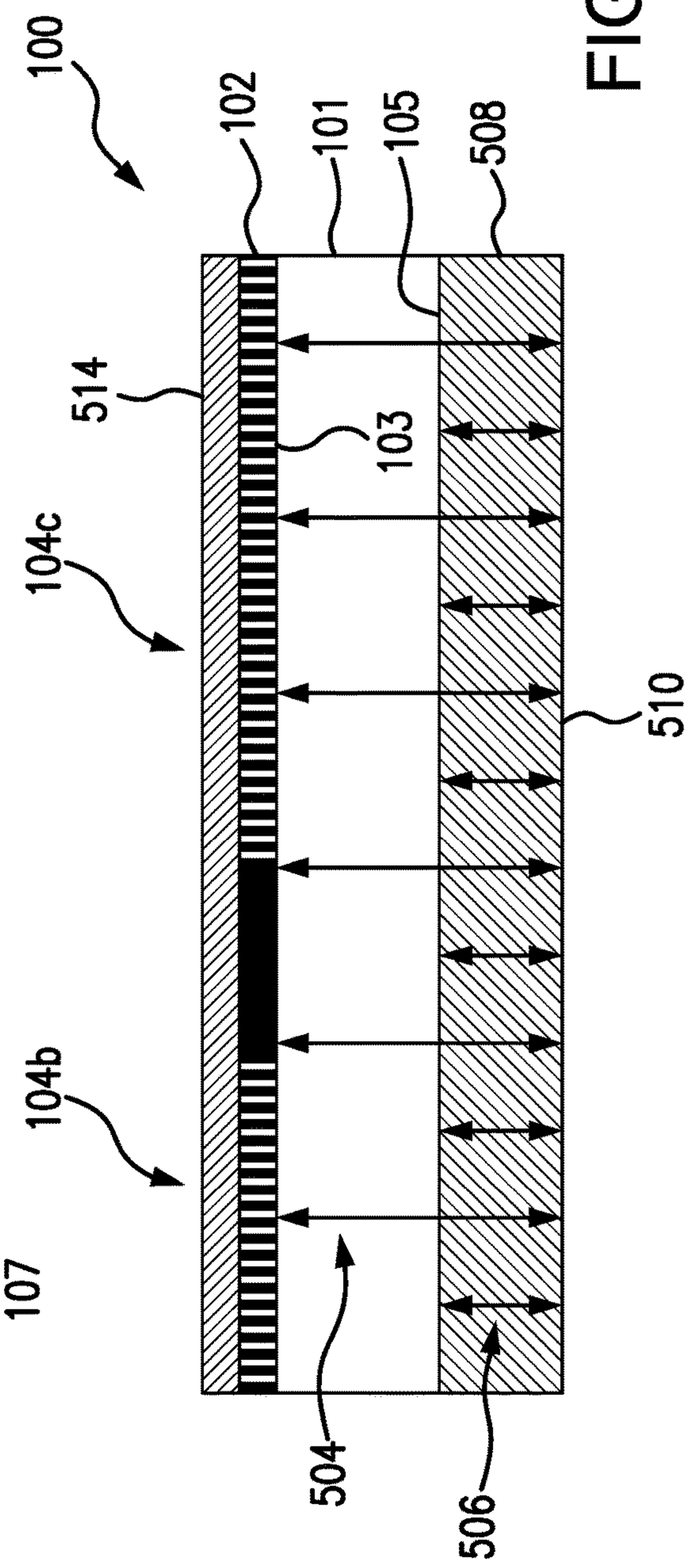

100
102
101
105
508
514
103
104c
104b
510
504
506

FIG. 5B

FIG. 5C

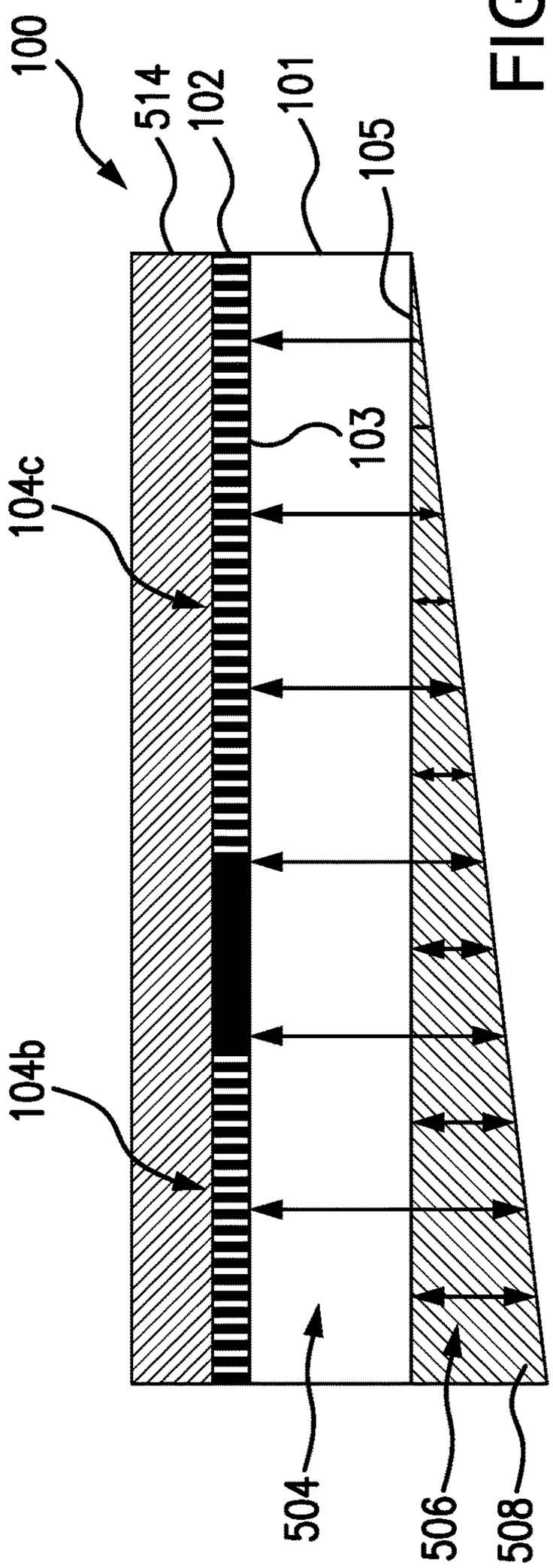
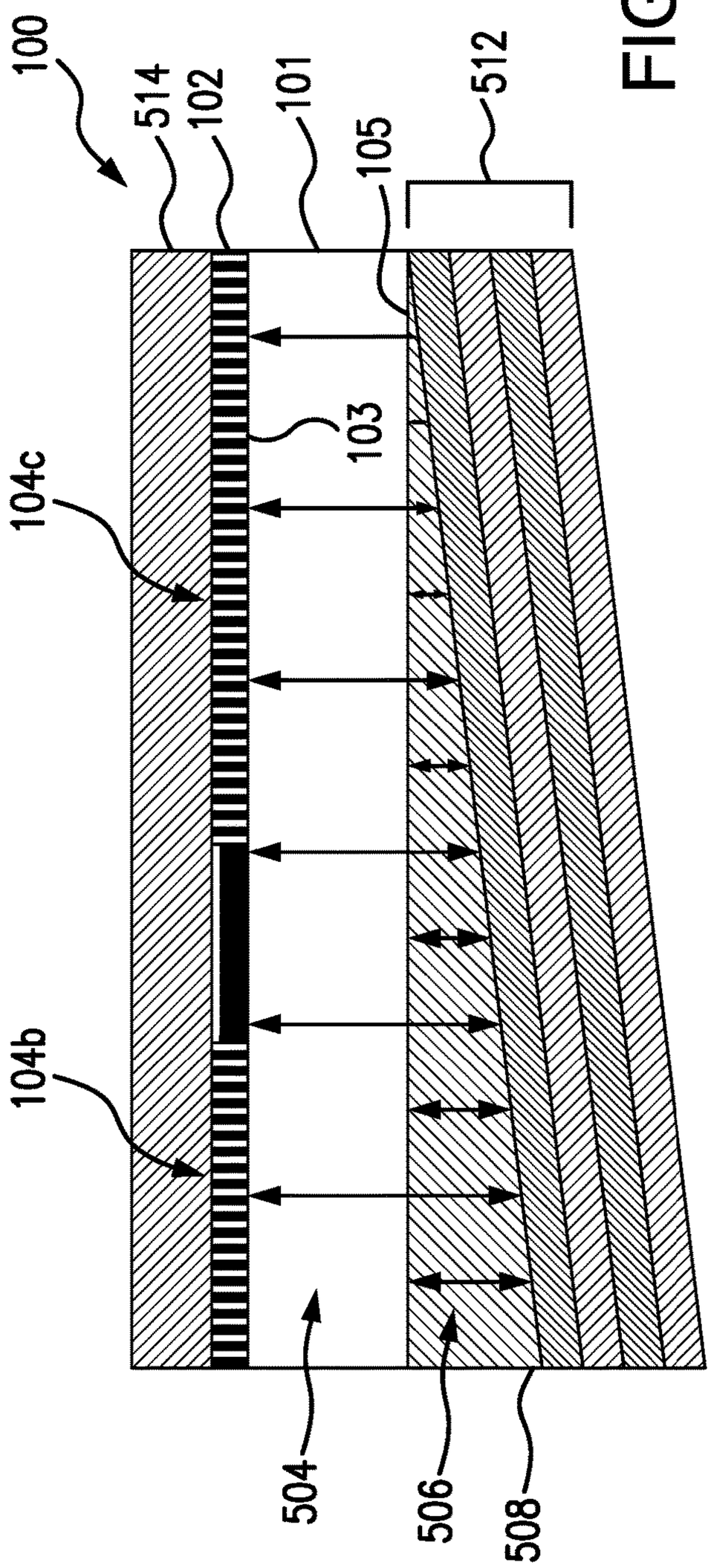

100
514
102
101
105
103
104c
104b
504
506
508

FIG. 5D


100
514
102
101
105
512
103
104c
104b
504
506
508

METHOD TO IMPROVE DISPLAY EFFICIENCY AND UNIFORMITY OF AR WAVEGUIDE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 63/365,447, filed May 27, 2022, which is incorporated by reference herein in its entirety.

BACKGROUND

Field

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein provide for methods to modify and engineer the effective thickness of an optical device substrate.

Description of the Related Art

Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as optical devices to display a virtual reality environment that replaces an actual environment.

Augmented reality, however, enables an experience in which a user can still see through the optical devices of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

Specifically, maintaining color uniformity and a high coupling efficiency of optical devices can be challenging. Color uniformity and coupling efficiency are related to the optical interference between different light paths within the optical device. Accordingly, what is needed in the art are improved methods of modulating the optical interference to enhance the light coupling efficiency to the outcoupler and optimizing the efficiency across the field of view.

SUMMARY

In one embodiment, an optical device is provided. The optical device includes a substrate having a substrate thickness distribution defined by a top surface of the substrate and a bottom surface of the substrate. The substrate thickness distribution varies along a first length parallel to the top surface and a second length perpendicular to the first length. The optical device further includes an index-matched layer disposed on the bottom surface of the substrate, the index-matched layer having an engineered thickness distribution defined by an exterior surface of the index-matched layer and the bottom surface of the substrate. The engineered thickness distribution varies along the first length and the second length perpendicular to the first length. The optical device further includes a plurality of optical device structures formed on the top surface of the substrate, a low index layer disposed over the plurality of optical device structures and an anti-reflective layer disposed over the exterior surface of the index-matched layer.

In another embodiment, a method of forming a design thickness distribution in an optical device is provided. The method includes measuring a substrate thickness distribution of a substrate defined by a distance between a top surface of the substrate and a bottom surface of the substrate along a first length parallel to the top surface and a second length perpendicular to the first length, disposing an index-matched layer on the bottom surface of the substrate, and etching the index-matched layer to have an engineered thickness distribution to form a design thickness distribution. The design thickness distribution is defined by the engineered thickness distribution and the substrate thickness distribution and the design thickness distribution varies along the first length and the second length.

In yet another embodiment, a method of forming a design thickness distribution in an optical device is provided. The method includes measuring a substrate thickness distribution of a substrate defined by a distance between a top surface of the substrate and a bottom surface of the substrate along a first length parallel to the top surface and a second length perpendicular to the first length, generating a phase map from the substrate thickness distribution across the bottom surface of the substrate, measuring a non-uniformity of pitch between adjacent optical device structures of a plurality of optical device structures disposed on the top surface of the substrate, generating an engineered phase profile by subtracting the phase map and the non-uniformity of pitch from a design phase map corresponding to a phase to be formed at each location of the optical device, and converting the engineered phase profile to an engineered thickness distribution. The method further includes disposing an index-matched layer on the bottom surface of the substrate to have the engineered thickness distribution to form a design thickness distribution. The design thickness distribution is defined by the engineered thickness distribution and the substrate thickness distribution and the design thickness distribution varies along the first length and the second length.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of scope, as the disclosure may admit to other equally effective embodiments.

FIG. **1** is a perspective, frontal view of an optical device according to embodiments described herein.

FIG. **2** is a flow diagram of a method of modifying the thickness of an optical device according to embodiments described herein.

FIGS. **3**A-**3**D are schematic, side views of an optical device during the method according to embodiments described herein.

FIG. **4** is a flow diagram of a method of modifying the thickness of an optical device according to embodiments described herein.

FIGS. **5**A-**5**D are schematic, side views of an optical device during the method according to embodiments described herein.

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

DETAILED DESCRIPTION

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein provide for methods to modify and engineer the effective thickness of an optical device substrate. The methods described herein for modulating optical interference of an optical device improve waveguide efficiency, color uniformity, and eyebox uniformity. The method includes removing or coating an extra dielectric layer on the optical device substrate. The thickness of the dielectric layer varies in the two dimensional plane parallel to the optical device substrate.

FIG. **1** is a perspective, frontal view of an optical device **100**. It is to be understood that the optical device **100** described below is an exemplary optical device. In one embodiment, which can be combined with other embodiments described herein, the optical device **100** is a waveguide combiner, such as an augmented reality waveguide combiner. The optical device **100** includes a plurality of optical device structures **102** disposed on a top surface **103** of a substrate **101**. The optical device structures **102** may be nanostructures having sub-micron dimensions, for example, nano-sized dimensions. In one embodiment, which can be combined with other embodiments described herein, regions of the optical device structures **102** correspond to one or more gratings **104**, such as a first grating **104***a*, a second grating **104***b*, and a third grating **104***c*. In another embodiment, which can combined with other embodiments described herein, the optical device **100** is a waveguide combiner that includes at least the first grating **104***a* corresponding to an input coupling grating and the third grating **104***c* corresponding to an output coupling grating. The waveguide combiner, according to the embodiment, which can be combined with other embodiments described herein, includes the second grating **104***b* corresponding to an intermediate grating.

While FIG. **1** depicts the optical device structures **102** as having square or rectangular shaped cross-sections, the cross-sections of the optical device structures **102** may have other shapes including, but not limited to, circular, triangular, elliptical, regular polygonal, irregular polygonal, and/or irregular shaped cross-sections. In some embodiments, which can be combined with other embodiments described herein, the cross-sections of the plurality of optical device structures **102** have different shaped cross-sections. In other embodiments, which can be combined with other embodiments described herein, the cross-sections of the optical device structures **102** have cross-sections with substantially the same shape. The plurality of optical device structures **102** may also be angled relative to the top surface **103** of the substrate **101**.

A light engine **110** is configured to direct a light beam **112** to the optical device **100**. In one example, the light engine **110** includes a microdisplay that provides a pattern to the optical device **100** via the light beam **112**. The light beam **112** undergoes total internal reflective through the optical device **100**. The optical device **100** directs the light beam **112** out to a human eye of a user of the optical device **100**. In order to improve coupling efficiency and color uniformity of the optical device **100**, the optical device **100** can be modulated to direct more of the light beam **112** in a first direction **114** compared to a second direction **116**. The first direction **114** corresponds to a direction toward the third grating **104***c*, while the second direction **116** corresponds to away from the third grating **104***c*. When the local substrate thickness variation is small (e.g., less than 500 nm of variation), the first direction **114** has a high probability to be destructive interference, while the second direction **116** has a high probability to be constructive interference. Constructive interference along the second direction **116** and destructive interference along the first direction **114** will decrease the coupling efficiency of the optical device **100**.

Methods **200** and **400** described below include removing or coating an extra dielectric layer on the optical device substrate. The thickness of the dielectric layer varies in the two dimensional plane parallel to the substrate **101**. The methods **200** and **400** described herein allow for adjusting the optical path of an optical device **100** after fabrication, improving one or more characteristics of the optical device **100**. For example, an optical device **100** that does not meet pre-determined thresholds of optical efficiency can be adjusted retroactively to achieve the threshold using embodiments described herein.

FIG. **2** is a flow diagram of a method **200** of modifying the thickness of an optical device **100**. FIGS. **3**A-**3**D are schematic, side views of an optical device **100** during the method **200**. The method **200** improves the display efficiency and display uniformity of the optical device **100**, while not damaging and/or decreasing the display resolution. The method **200** also will save optical devices **100** with low efficiency or display uniformity below a pre-determined threshold. The optical device **100** is already formed but may have a lower efficiency due to thickness of the optical device or pitch uniformity of the optical device structures. Adjusting the thickness variation will allow light to go in the correct optical path towards an output coupling grating, for example, the third grating **104***c*. The phase profile is adjusted by changing the thickness of the optical device **100**.

As shown in FIGS. **3**A-**3**D, the optical device **100** includes a plurality of optical device structures **102** formed on a substrate **101**. The method **200** is applied to optical device structures **102** with a pitch uniformity and angle uniformity that is well-controlled (e.g., high uniformity). The pitch (see FIG. **5**A) of the optical device structures **102** is defined as the distance between leading edges or trailing edges of adjacent optical device structures **102**. The optical device structures **102** are well-controlled if the ratio of standard deviation of the pitch to the pitch nominal value is less than about 10^{-4}.

The substrate **101** includes a bottom surface **105** and a top surface **103**. Regions of the optical device structures **102** correspond to one or more gratings **104**, such as a first grating **104***a*, a second grating **104***b*, and a third grating **104***c*. Prior to the method **200**, the optical device **100** is inspected. For example, a metrology process inspects the optical device **100** to determine if the optical device **100** meets a pre-determined threshold for display efficiency and display uniformity.

At operation **201**, as shown in FIG. **3**A, a substrate thickness distribution **302** of the substrate **101** is measured. The substrate thickness distribution **302** is measured with a laser interferometer. The substrate thickness distribution **302** is defined by the distance between the top surface **103** of the substrate and the bottom surface **105** along a first length **107** of the substrate **101**. The first length **107** is parallel to the top surface **103** of the substrate **101**. The substrate thickness

distribution **302** can also vary along a second length **109** perpendicular to the first length **107**. The substrate thickness distribution **302** is collected as data and sent to a controller or computer.

At operation **202**, a design thickness distribution **304** is determined. The design thickness distribution **304** is the target thickness distribution that is to be formed from the substrate thickness distribution **302**. The design thickness distribution **304** can vary across the first length **107** of the substrate in a linear or nonlinear distribution. The design thickness distribution **304** can also vary along a direction perpendicular to the first length **107**, for example, the design thickness distribution **304** can vary along the second length **109**.

At operation **203**, an engineered thickness distribution **306** is determined. The engineered thickness distribution **306** is determined by subtracting the design thickness distribution **304** at each position along the first length **107** from the substrate thickness distribution **302** at each position along the first length **107**. The engineered thickness distribution can also be determined to vary along a direction perpendicular to the first length **107**, for example, the design thickness distribution **304** can vary along the second length **109**. The engineered thickness distribution **306** is calculated with physical optics and ray tracing optics models, with the full optical device **100** design information, for example, critical dimensions of the optical device structures **102**, height, pitch, and angle of the optical device structures **102**, optical material properties of the optical device **100**.

At operation **204**, as shown in FIG. **3**B, an index-matched layer **308** with the engineered thickness distribution **306** is disposed to form the design thickness distribution **304**. The design thickness distribution **304** is different than the substrate thickness distribution **302**. The index-matched layer **308** is disposed over the bottom surface **105** of the substrate **101**. The index-matched layer **308** has a first refractive index that matches or substantially matches a second refractive index of the substrate **101**. For example, the first refractive index and the second refractive index are within about 5% of each other. The refractive index of the substrate **101** and the index-matched layer **308** is between about 1.7 and about 2.9. The difference between the refractive index of the substrate **101** and the index-matched layer **308** is between about and about 0.1.

The substrate **101** and the index-matched layer **308** may be formed from any suitable material, provided that the substrate **101** can adequately transmit light in a targeted wavelength or wavelength range and can serve as an adequate support for the optical devices **100**. The substrate **101** may be a material including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, and combinations thereof. In some embodiments, which may be combined with other embodiments described herein, the substrate **101** includes a transparent material. In one example, the substrate **101** includes one or more of high index glass, silicon dioxide (SiO_2), fused silica, quartz, silicon carbide (SiC), $LiNbO_3$, diamond (C), gallium nitride (GaN), sapphire, or combinations thereof. The index-matched layer **308** is a deposited thin film containing silicon nitride (SiN), titanium oxide (TiOx), tantalum oxide (TaOx), niobium oxide (NbOx), zirconium oxide (ZrOx), or a synthesized nanoparticle material. For example, the index-matched layer **308** is titanium oxide (TiO_2) or zirconium oxide (ZrO_2) material with nanoparticles embedded in a polymer matrix. In one example, the substrate **101** and the index-matched layer **308** are different materials. In another example, the substrate **101** and the index-matched layer **308** are the same material.

The substrate **101** and the index-matched layer **308** combine to form the design thickness distribution **304**. The design thickness distribution **304** is defined by the distance between the top surface **103** of the substrate **101** an exterior surface **310** of the index-matched layer **308** along the first length **107** and the second length **109** perpendicular to the first length **107**. The exterior surface **310** is facing away from the substrate **101**. The design thickness distribution **304** and the engineered thickness distribution **306** are not limited by FIGS. **3**A-**3**D and may be distributed as determined to improve optical device performance.

In a first embodiment, which can be combined with other embodiments described herein, the index-matched layer **308** is disposed over the bottom surface **105** of the substrate **101**. The index-matched layer **308** is selectively etched to form the engineered thickness distribution **306**. The selective etch includes at least one of ion implantation, ion beam etching (IBE), reactive ion etching (RIE), directional RIE, plasma etching, and thermal atomic layer etching. The engineered thickness distribution **306** in combination with the substrate thickness distribution **302** forms the design thickness distribution **304**. In a second embodiment, which can be combined with other embodiments described herein, the index-matched layer **308** is selectively deposited. For example, the index-matched layer **308** is selectively deposited with an inkjet printing process to form the engineered thickness distribution **306**. The engineered thickness distribution **306** in combination with the substrate thickness distribution **302** forms the design thickness distribution **304**.

At optional operation **205**, as shown in FIG. **3**C, an anti-reflective layer **312** is disposed over the exterior surface **310** of the index-matched layer **308**. The anti-reflective layer **312** is conformal to the index-matched layer **308**. In one embodiment, the anti-reflective layer **312** includes multiple stacked layers of material. For example, the layer of the anti-reflective material include one or more of SiOx, ZrOx and TiOx. The anti-reflective layer **312** may include an alternating low index layer and high index layer. The low index layer has a refractive index of between about 1.4 and about 1.7. The high index layer has a refractive index greater than about 2. The low index layer is a SiOx material. The high index layer is a metal oxide material. The anti-reflective layer **312** is configured to increase the efficiency of the optical device by reducing light lost due to reflection. The anti-reflective layer **312** is disposed via an ALD process.

At optional operation **206**, as shown in FIG. **3**D, a low index layer **314** is disposed over the plurality of optical device structures **102**. The low index layer **314** is a SiOx material. The low index layer is utilized for improving anti-reflective properties. The low index layer **314** has a refractive index of about 1.4 to about 1.7.

By forming the design thickness distribution **304**, the phase change of the optical device **100** is adjusted to modulate the optical interference between different light paths. Forming the design thickness distribution **304** will enhance light coupling efficiency to the output coupling grating, for example, the third grating **104***c*, and optimize efficiency across the optical device **100**. The method **200** can be utilized to allow already manufactured optical devices **100** that do not predetermined efficiency thresholds to meet the predetermined efficiency thresholds.

FIG. **4** is a flow diagram of a method **400** of modifying the thickness of an optical device **100**. FIGS. **5**A-**5**D are schematic, side views of an optical device **100** during the method **400**. The method **400** improves the display efficiency and

display uniformity of the optical device **100**, while not damaging and/or reducing the display resolution. The method **400** also will save optical devices **100** with low efficiency or display uniformity below a pre-determined threshold. The optical device **100** is already formed but may have a lower efficiency due to thickness of the optical device or pitch uniformity of the optical device structures. Adjusting the thickness variation will allow light to go in the correct optical path towards an output coupling grating, for example, the third grating **104***c*. The phase profile is adjusted by changing the thickness of the optical device **100**.

As shown in FIG. **5**A, the optical device **100** includes a plurality of optical device structures **102** formed on a substrate **101**. The method **400** is applied to optical device structures **102** with a pitch uniformity and angle uniformity that is not controlled (e.g., low uniformity). The optical device structures **102** are considered to be well-controlled if the ratio of standard deviation of the pitch **516** to the pitch **516** nominal value is greater than about 10^{-4}.

The substrate **101** includes a bottom surface **105** and a top surface **103**. Regions of the optical device structures **102** correspond to one or more gratings **104**, such as a first grating **104***a*, a second grating **104***b*, and a third grating **104***c*. An anti-reflective layer **512** is disposed over the bottom surface **105** of the substrate **101**. A low index layer **514** is disposed over the plurality of optical device structures **102**.

Prior to the method **400**, the optical device **100** is inspected. For example, a metrology process inspects the optical device **100** to determine if the optical device **100** meets a pre-determined threshold for display efficiency and display uniformity. If the optical device **100** does not meet the pre-determined threshold, the method **400** may be performed. The method **400** may be performed to restore the optical device **100** to meet the pre-determined threshold.

At operation **401**, as shown in FIG. **5**A, a substrate thickness distribution **502** of the substrate **101** is measured and a phase map is generated. The substrate thickness distribution **502** is measured with a laser interferometer. The substrate thickness distribution **502** is defined by the distance between the top surface **103** of the substrate **101** and the bottom surface **105** along a first length **107** of the substrate **101** and perpendicular to the first length **107**, for example, along a second length **109** perpendicular to the first length **107**. The substrate thickness distribution **502** is collected as data and sent to a controller or computer. Based on the substrate thickness distribution **502**, a phase map is generated. The phase map specifies the phase at each location on the substrate **101** across the bottom surface **105** of the substrate **101**. The phase map is generated by determining the phase change at each location. The phase change is determined by obtaining the thickness variation at each location and dividing by wavelength of light to transmit times 2 pi.

At operation **402**, a design thickness distribution **504** is determined and a design phase map is generated. The design thickness distribution **504** is the target thickness distribution that is to be formed from the substrate thickness distribution **502**. The design thickness distribution **504** can vary across the first length **107** and along the second length **109** perpendicular to the first length **107** of the substrate **101** in a linear or nonlinear distribution. The design phase map is generated from the design thickness distribution **504**. The design phase map specifies the phase that will be formed at each location on the substrate **101** in the final optical device **100**. The design phase map is generated by a waveguide design software application.

At operation **403**, non-uniformity of pitch **516** of the plurality of optical device structures **102** is measured. The pitch **516** is defined as the distance between leading edges or trailing edges of adjacent optical device structures **102**. The pitch **516** of each of the adjacent optical device structures **102** is measured to determine the degree of non-uniformity of the pitch **516** across the substrate **101**. The pitch **516** at each location across the substrate **101** is mapped out. The uniformity of the optical device structures **102** is defined by the ratio of standard deviation of the pitch **516** to the nominal value of the pitch **516**.

At operation **404**, an engineered phase profile is generated. The engineered phase profile is the change to the phase of the phase map to form the design phase map. The engineered phase profile is generated by subtracting the phase map and the pitch **516** non-uniformity from the design phase map at each location across the optical device **100**. The engineered phase profile can be generated with an engineered phase at each location along the first length **107** and a direction perpendicular to the first length **107**, for example, along the second length **109**.

At operation **405**, the engineered phase profile is converted to an engineered thickness distribution **506**. The engineered phase profile is converted to the engineered thickness distribution **506** by dividing the phase change at each location by wavelength of light to transmit times 2 pi.

The engineered thickness distribution **506** is determined by subtracting the design thickness distribution **504** at each position along the first length **107** from the substrate thickness distribution **502** at each position along the first length **107** and perpendicular to the first length **107**, for example, along the second length **109**. The engineered thickness distribution **506** is calculated with physical optics and ray tracing optics models, with the full optical device **100** design information (e.g., critical dimensions of the optical device structures **102**, height, pitch, and angle of the optical device structures **102**, optical material properties of the optical device **100**).

At operation **406**, as shown in FIG. **5**B, the anti-reflective layer **512** is removed. The anti-reflective layer **512** is removed via an etch process. At operation **407**, as shown in FIGS. **5**B and **5**C, an index-matched layer **508** is disposed. The index-matched layer **508** is disposed over the bottom surface **105** of the substrate **101**. The index-matched layer **508** has a first refractive index that matches or substantially matches a second refractive index of the substrate **101**.

In a first embodiment shown in FIG. **5**B and FIG. **5**C, which can be combined with other embodiments described herein, the index-matched layer **508** is disposed over the bottom surface **105** of the substrate **101** (see FIG. **5**B). The index-matched layer **508** is selectively etched to form the engineered thickness distribution **506**. The selective etch includes at least one of ion implantation, ion beam etching (IBE), reactive ion etching (RIE), directional RIE, plasma etching, and thermal atomic layer etching. The engineered thickness distribution **506** in combination with the substrate thickness distribution **502** forms the design thickness distribution **504**.

In a second embodiment shown in FIG. **5**C, which can be combined with other embodiments described herein, the index-matched layer **508** is selectively deposited. For example, the index-matched layer **508** is selectively deposited with an inkjet printing process to form the engineered thickness distribution **506**. In other words, the index-matched layer **508** is deposited to have the engineered thickness distribution **506** without an etching process. As such, the operation shown in FIG. **5**B is optional. The

engineered thickness distribution **506** in combination with the substrate thickness distribution **502** forms the design thickness distribution **504**.

The substrate **101** and the index-matched layer **508** combine to form the design thickness distribution **504**. The design thickness distribution **504** is defined by the distance between the top surface **103** of the substrate **101** and an exterior surface **510** of the index-matched layer **508** along the first length **107** and perpendicular to the first length **107**, for example, along the second length **109**. The design thickness distribution **504** is different than the substrate thickness distribution **502**. The exterior surface **510** is facing away from the substrate **101**. The design thickness distribution **504** and the engineered thickness distribution **506** are not limited by FIGS. **5**A-**5**D and may be distributed as determined to improve optical device performance.

At optional operation **408**, as shown in FIG. **5**D, the anti-reflective layer **512** is disposed over the exterior surface **510** of the index-matched layer **508**. The anti-reflective layer **512** is conformal to the index-matched layer **508**. In one embodiment, the anti-reflective layer **512** includes multiple stacked layers of material. The anti-reflective material may include an alternating low index layer and high index layer. The anti-reflective layer **512** is configured to increase the efficiency of the optical device by reducing light lost due to reflection. The anti-reflective layer **512** is disposed via an ALD process.

By forming the design thickness distribution **504**, the phase change of the optical device **100** is adjusted to modulate the optical interference between different light paths. Forming the design thickness distribution **504** will enhance light coupling efficiency to the output coupling grating, for example, the third grating **104***c*, and optimize efficiency across the optical device **100**. The method **400** can be utilized to allow already manufactured optical devices **100** that do not meet predetermined efficiency thresholds to meet the predetermined efficiency thresholds.

In summation, methods of modifying and engineering the effective thickness of an optical device substrate are provided. The methods provide for depositing a material that is index-matched to the substrate to alter a thickness distribution of the optical device. By adjusting the thickness distribution, the optical path of light is modulated to direct the light to the output coupling grating. The methods improve the display efficiency and uniformity without damaging the display resolution. The methods also are used to alter optical devices that do not meet pre-determined efficiency thresholds such that the optical devices will meet the pre-determined thresholds.

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 method of forming a design thickness distribution in an optical device, comprising:

measuring a substrate thickness distribution of a substrate defined by a distance between a top surface of the substrate and a bottom surface of the substrate along a first length parallel to the top surface and a second length perpendicular to the first length;

generating a phase map from the substrate thickness distribution across the bottom surface of the substrate;

measuring a non-uniformity of pitch between adjacent optical device structures of a plurality of optical device structures disposed on the top surface of the substrate;

generating an engineered phase profile by subtracting the phase map and the non-uniformity of pitch from a design phase map corresponding to a phase to be formed at each location of the optical device;

converting the engineered phase profile to an engineered thickness distribution; and

disposing an index-matched layer on the bottom surface of the substrate to have the engineered thickness distribution to form a design thickness distribution, wherein the design thickness distribution is defined by the engineered thickness distribution and the substrate thickness distribution, wherein the design thickness distribution varies along the first length and the second length.

2. The method of claim **1**, wherein the index-matched layer is disposed via an inkjet printing process to have the engineered thickness distribution.

3. The method of claim **1**, wherein the substrate has a first refractive index and the index-matched layer has a second refractive index, wherein the second refractive index substantially matches the first refractive index.

4. The method of claim **1**, further comprising removing an anti-reflective layer from the bottom surface of the substrate before disposing the index-matched layer.

5. The method of claim **4**, further comprising disposing the anti-reflective layer over an exterior surface of the index-matched layer via an ALD process.

6. The method of claim **4**, wherein the anti-reflective layer includes two or multiple stacked layers of material.

7. The method of claim **4**, wherein the anti-reflective layer includes an alternating low index layer and high index layer, wherein the low index layer has a refractive index of between about 1.4 and about 1.7 and the high index layer has a refractive index of greater than about 2.0.

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