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(54) **SYSTEMS AND METHODS OF BROADBAND ACHROMATIC METASURFACE WAVEPLATES**

(71) Applicant: **PRESIDENT AND FELLOWS OF HARVARD COLLEGE**, Cambridge, MA (US)

(72) Inventors: **Xinghui YIN**, Cambridge, MA (US); **Federico CAPASSO**, Cambridge, MA (US)

(73) Assignee: **PRESIDENT AND FELLOWS OF HARVARD COLLEGE**, Cambridge, MA (US)

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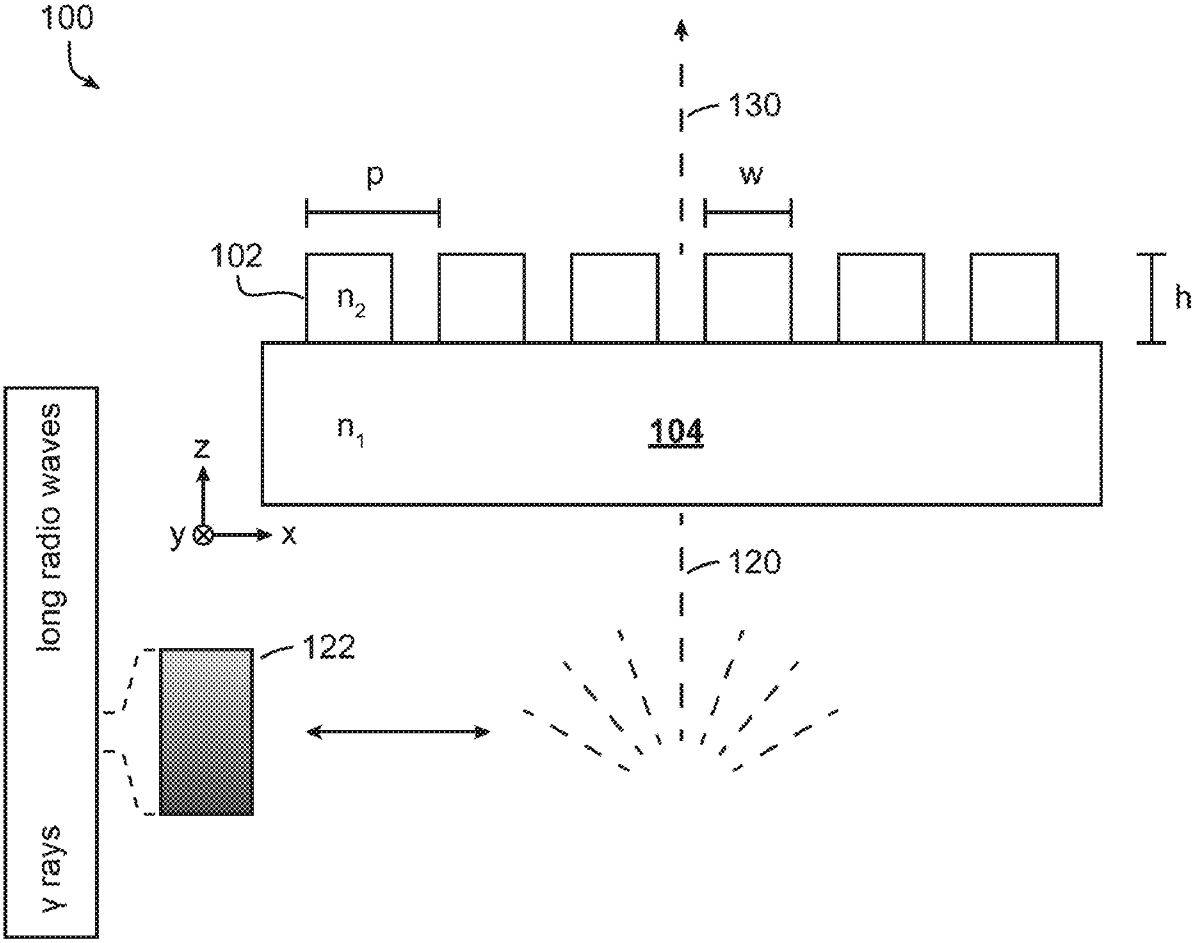
CPC *G02B 1/007* (2013.01)

(57) **ABSTRACT**

Disclosed is a broadband achromatic metasurface waveplate including a device that includes a plurality of nanostructures physically coupled to a substrate and formed at least partially of a dielectric material having a first refractive index and an anti-reflective film applied to a surface of the device. The anti-reflective film may include a material having a second refractive index that is less than the first refractive index. The device and the anti-reflective film may modify incident light with wavelengths extending over a bandwidth of at least 100 nanometers to impart a substantially uniform phase retardation across the wavelengths and a transmittance of at least 90 percent across the wavelengths.



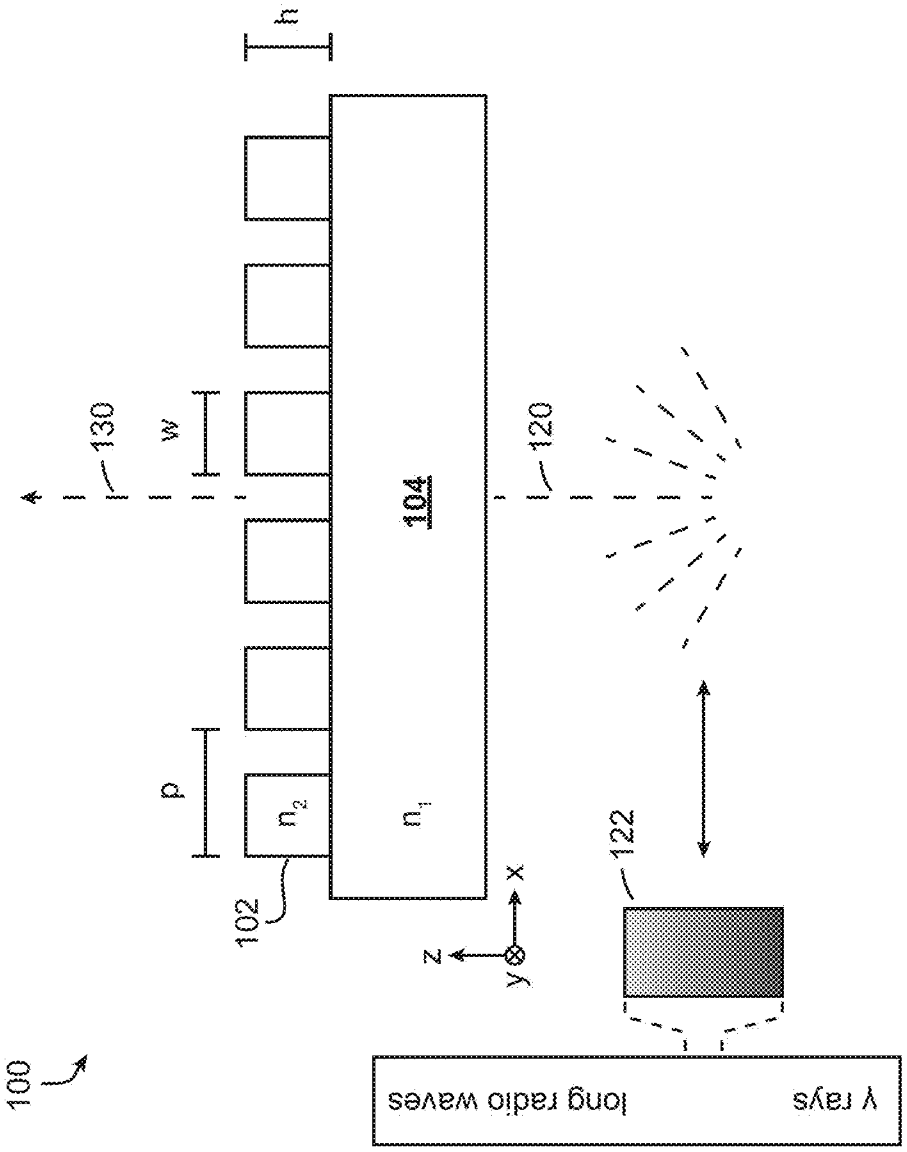


FIG. 1

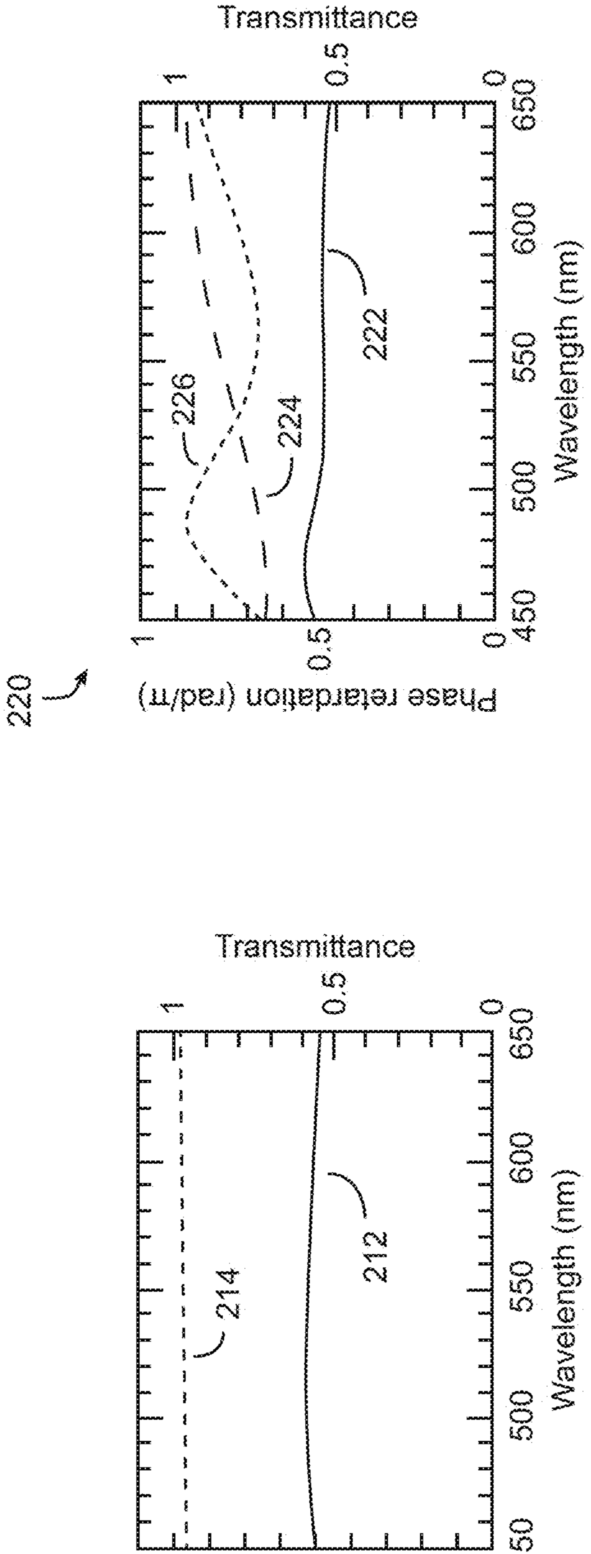

210
Phase retardation (rad/π)
1
0.5
0
Transmittance
1
0.5
0
450
500
550
600
650
Wavelength (nm)
212
214
220
Phase retardation (rad/π)
1
0.5
0
Transmittance
1
0.5
0
450
500
550
600
650
Wavelength (nm)
222
224
226

FIG. 2

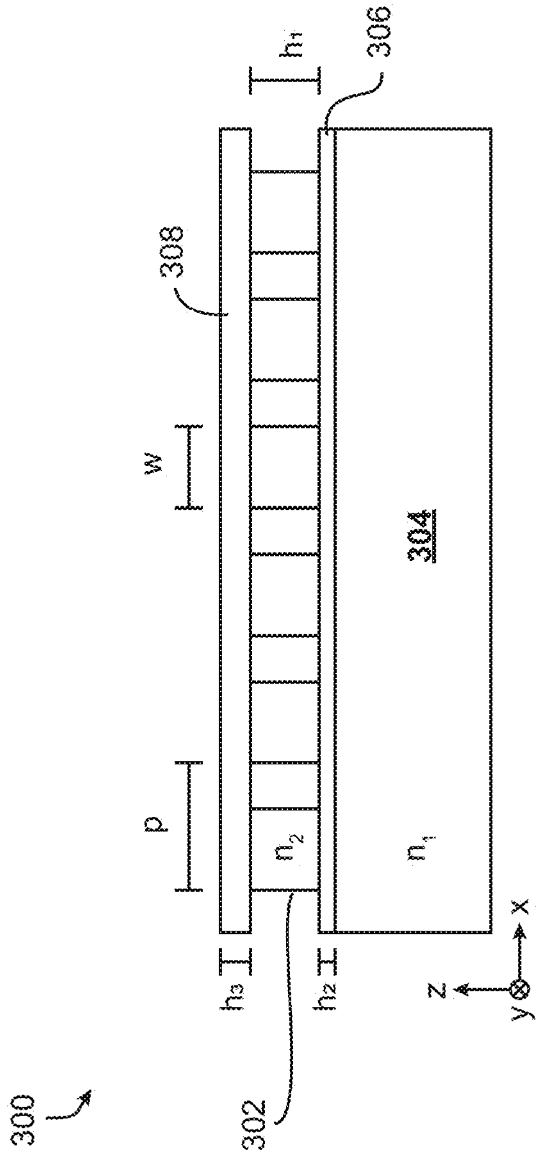


FIG. 3A

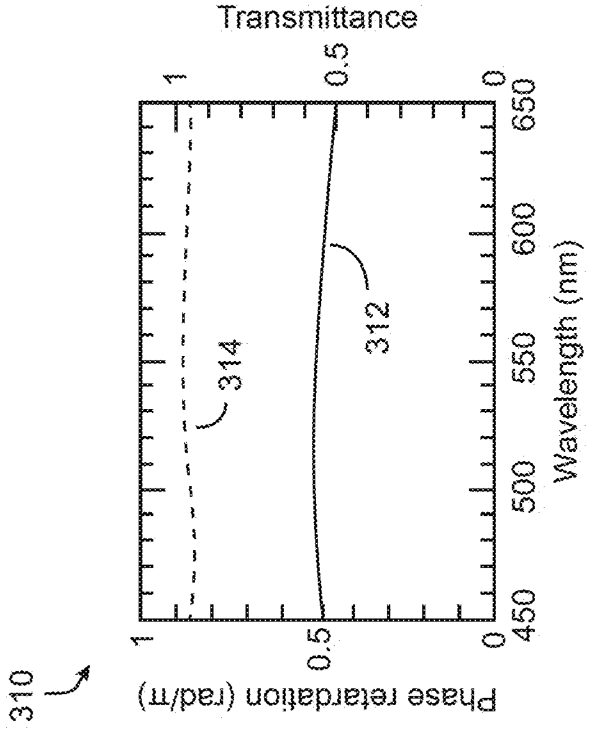

310
Transmittance
1
0.5
0
Phase retardation (rad/π)
1
0.5
0
450
500
550
600
650
Wavelength (nm)
314
312

FIG. 3B

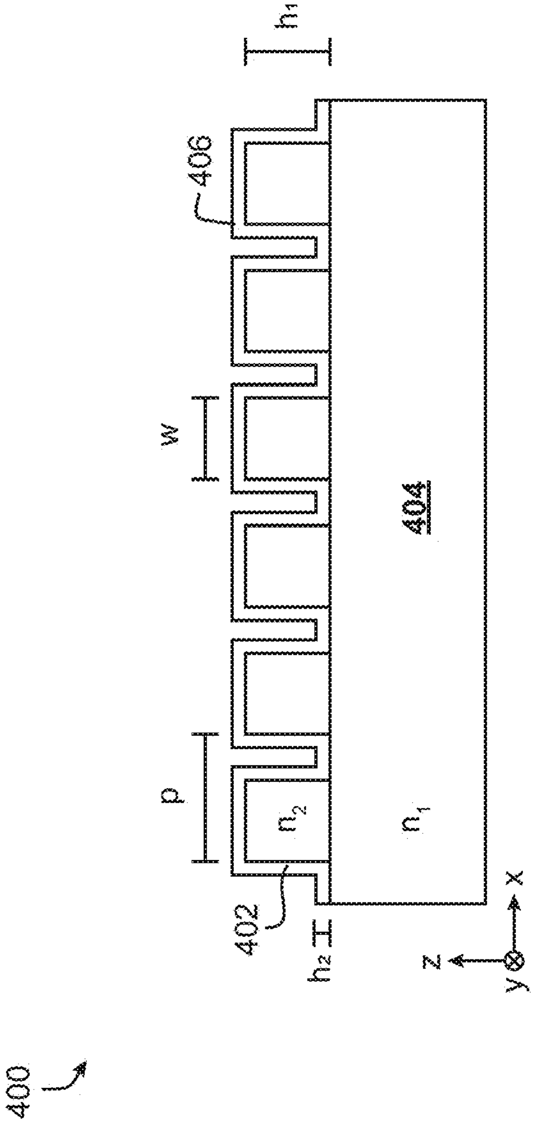


FIG. 4A

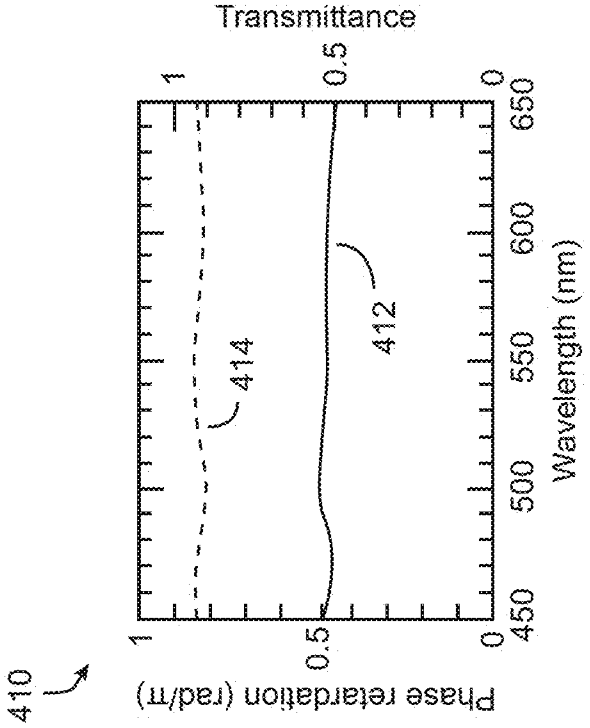

410
Transmittance
1
0.5
0
Phase retardation (rad/π)
1
0.5
0
450
500
550
600
650
Wavelength (nm)
414
412

FIG. 4B

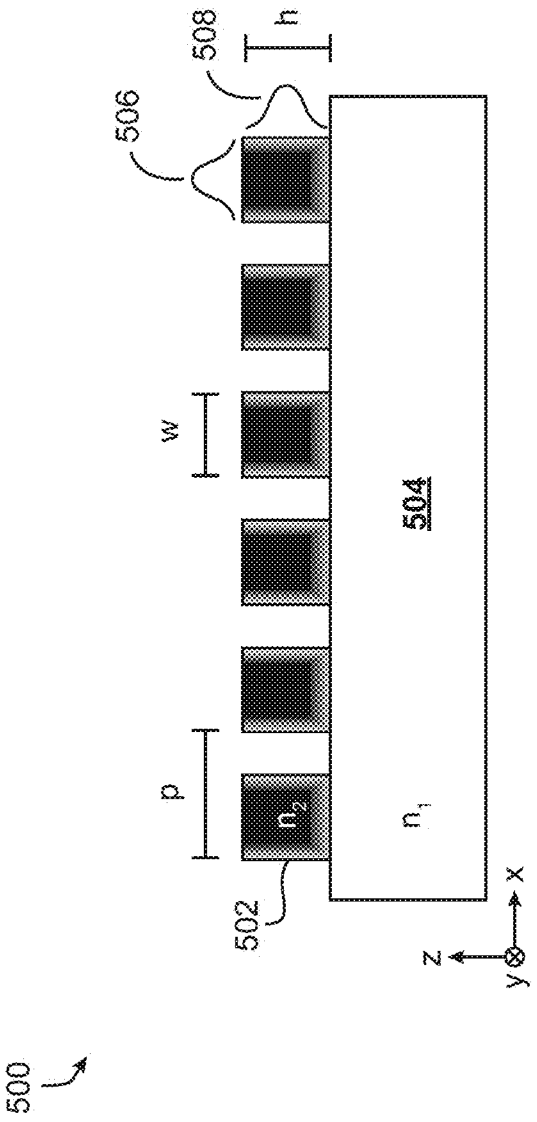


FIG. 5A

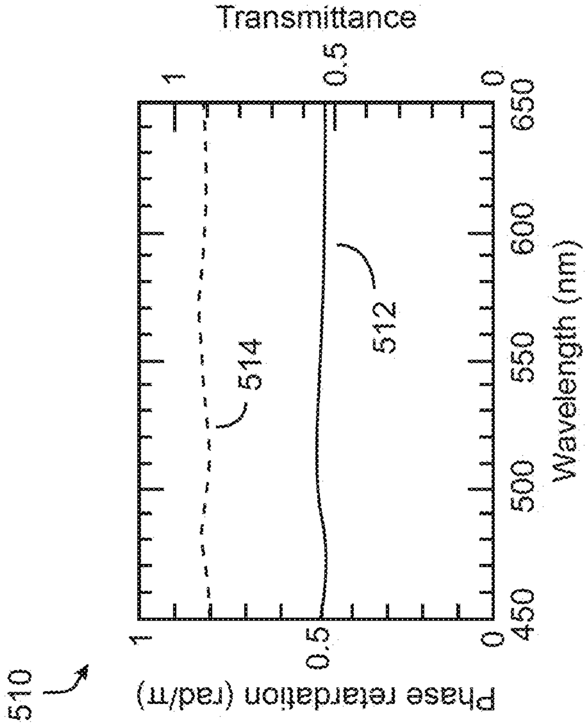

510
Phase retardation (rad/π)
1
0.5
0
Transmittance
1
0.5
0
450
500
550
600
650
Wavelength (nm)
514
512

FIG. 5B

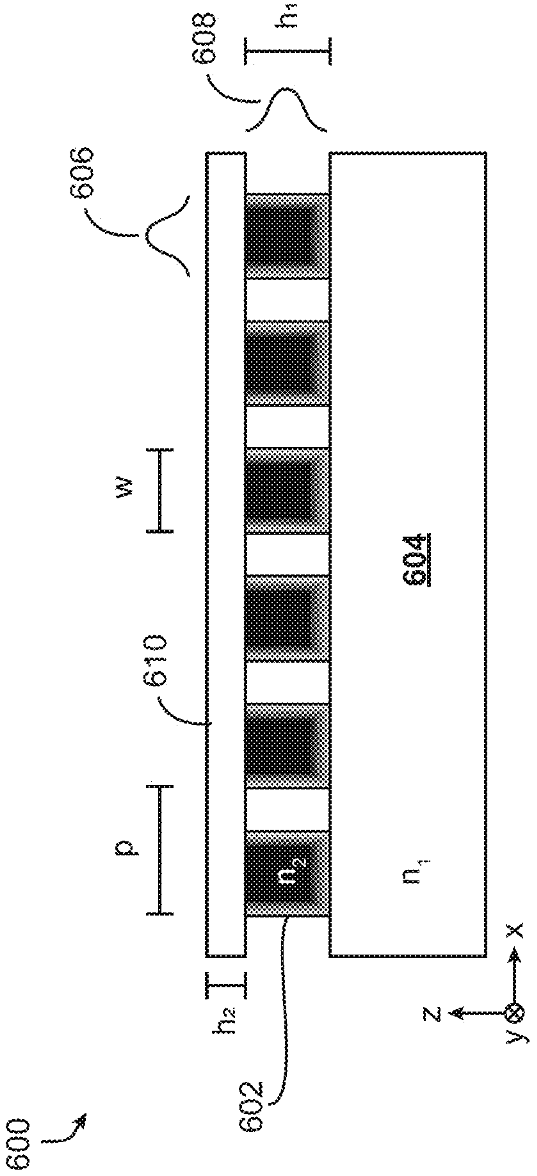


FIG. 6A

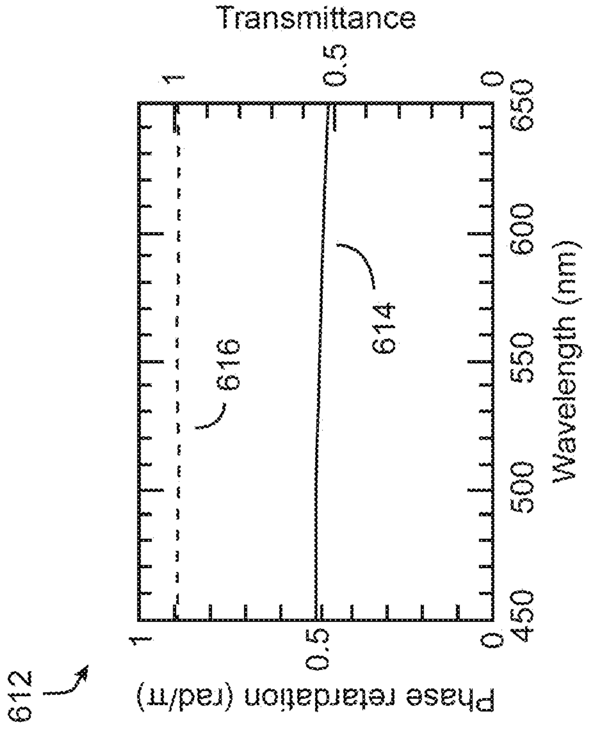

612
Transmittance
1
0.5
0
Phase retardation (rad/π)
1
0.5
0
Wavelength (nm)
450
500
550
600
650
616
614

FIG. 6B

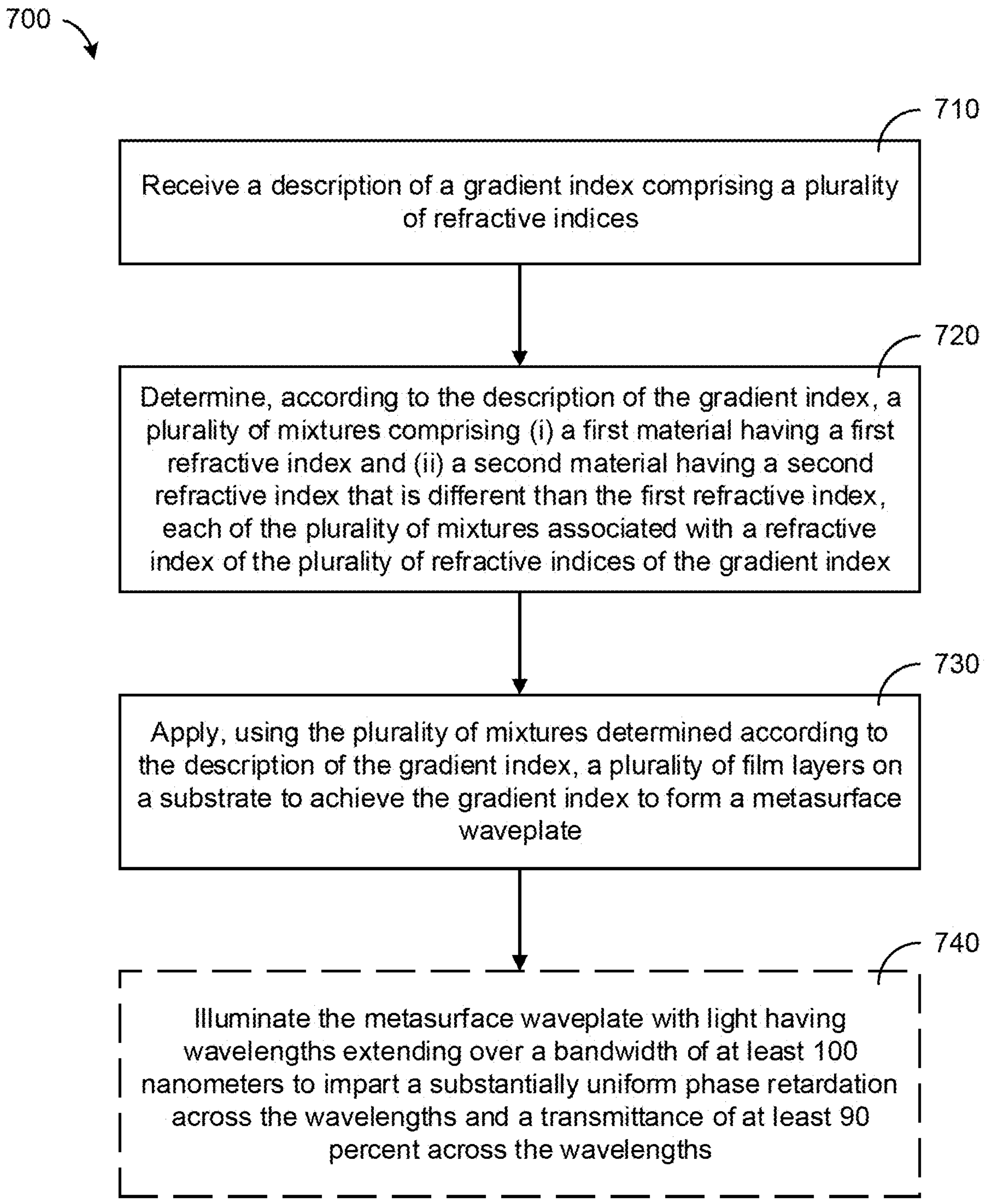

700
710
Receive a description of a gradient index comprising a plurality of refractive indices
720
Determine, according to the description of the gradient index, a plurality of mixtures comprising (i) a first material having a first refractive index and (ii) a second material having a second refractive index that is different than the first refractive index, each of the plurality of mixtures associated with a refractive index of the plurality of refractive indices of the gradient index
730
Apply, using the plurality of mixtures determined according to the description of the gradient index, a plurality of film layers on a substrate to achieve the gradient index to form a metasurface waveplate
740
Illuminate the metasurface waveplate with light having wavelengths extending over a bandwidth of at least 100 nanometers to impart a substantially uniform phase retardation across the wavelengths and a transmittance of at least 90 percent across the wavelengths

FIG. 7

SYSTEMS AND METHODS OF BROADBAND ACHROMATIC METASURFACE WAVEPLATES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application 63/242,932, filed Sep. 10, 2021, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] Metasurfaces are optical elements to manipulate electromagnetic waves such as light. Metasurfaces may enable various applications that may be impractical to achieve with traditional diffractive lenses. For example, metasurfaces often have a smaller form factor than traditional diffractive lenses and are therefore suited to micro or lightweight applications.

SUMMARY

[0003] One embodiment of the present disclosure is a broadband achromatic metasurface waveplate including a device comprising a plurality of nanostructures physically coupled to a substrate and formed at least partially of a dielectric material having a first refractive index and an anti-reflective film applied to a surface of the device. The anti-reflective film may include a material having a second refractive index that is less than the first refractive index. The device and the anti-reflective film may modify incident light with wavelengths extending over a bandwidth of at least 100 nanometers to impart a substantially uniform phase retardation across the wavelengths and a transmittance of at least 90 percent across the wavelengths.

[0004] In some embodiments, the second refractive index is substantially equal to the square root of the product of the first refractive index and a third refractive index. In some embodiments, the wavelengths extend between at least 450 nanometer and 650 nanometer. In some embodiments, the substantially uniform phase retardation varies within a range of 0.08 radians/a. In some embodiments, the dielectric material includes TiO_2 and wherein the material includes Al_2O_3.

[0005] Another embodiment of the present disclosure is a metasurface waveplate including a substrate having a first refractive index and a plurality of nanostructures coupled to the substrate and formed at least partially of a dielectric material having a second refractive index. The metasurface waveplate may include a first anti-reflective film positioned between the substrate and the plurality of nanostructures, the first anti-reflective film having a third refractive index that is greater than the first refractive index and less than the second refractive index. The metasurface waveplate may include a second anti-reflective film positioned at least partially on a surface of the plurality of nanostructures, the second anti-reflective film having a fourth refractive index that is less than the second refractive index. The substrate, the plurality of nanostructures, the first anti-reflective film, and the second anti-reflective film may modify incident light with wavelengths extending over a bandwidth of at least 100 nanometers to impart a substantially uniform phase retardation across the wavelengths and a transmittance of at least 90 percent across the wavelengths.

[0006] In some embodiments, the third refractive index is substantially equal to the square root of the product of (i) the first refractive index and (ii) an effective index along a slow axis of a device comprising the substrate and the plurality of nanostructures. In some embodiments, the fourth refractive index is substantially equal to the square root of the product of (i) an effective index along a slow axis of a device comprising the substrate and the plurality of nanostructures and (ii) a fifth refractive index. In some embodiments, the wavelengths extend between at least 450 nanometer and 650 nanometer. In some embodiments, the substantially uniform phase retardation varies within a range of 0.08 radians/it. In some embodiments, the dielectric material includes TiO_2 and wherein the first anti-reflective film includes Al_2O_3. In some embodiments, the dielectric material includes TiO_2 and wherein the second anti-reflective film includes Sift.

[0007] Another embodiment of the present disclosure is a metasurface waveplate including a device comprising a plurality of nanostructures physically coupled to a substrate having a first refractive index, each nanostructure of the plurality of nanostructures having a radial gradient index centered on the nanostructure, wherein the radial gradient index includes an upper refractive index and a lower refractive index, and wherein the upper refractive index is greater than the first refractive index, wherein device modifies incident light with wavelengths extending over a bandwidth of at least 100 nanometers to impart a substantially uniform phase retardation across the wavelengths and a transmittance of at least 90 percent across the wavelengths.

[0008] In some embodiments, the wavelengths extend between at least 450 nanometer and 650 nanometer. In some embodiments, the substantially uniform phase retardation varies within a range of 0.08 radians/it. In some embodiments, the metasurface waveplate further comprises an anti-reflective film applied to a surface of the device, the anti-reflective film comprising a material having a second refractive index that is less than the upper refractive index. In some embodiments, the second refractive index is substantially equal to the square root of the product of (i) a refractive index associated with the plurality of nanostructures and (ii) a third refractive index. In some embodiments, the material includes Al_2O_3. In some embodiments, the radial gradient index comprises a combination of (i) TiO_2 and (ii) at least one of MgF_2 or SiO_2.

[0009] Another embodiment of the present disclosure is a method for manufacturing a metasurface waveplate including receiving a description of a gradient index comprising a plurality of refractive indices, determining, according to the description of the gradient index, a plurality of mixtures comprising (i) a first material having a first refractive index and (ii) a second material having a second refractive index that is different than the first refractive index, each of the plurality of mixtures associated with a refractive index of the plurality of refractive indices, and applying, using the plurality of mixtures according to the description of the gradient index, a plurality of film layers on a substrate to achieve the gradient index.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] For a better understanding of the nature and objects of some embodiments of this disclosure, reference should be made to the following detailed description taken in conjunction with the accompanying drawings.

[0011] FIG. **1** is a block diagram illustrating a broadband achromatic metasurface waveplate, according to an example embodiment;

[0012] FIG. **2** illustrates optical response characteristics associated with the broadband achromatic metasurface waveplate of FIG. **1**, according to an example embodiment;

[0013] FIG. **3**A is a block diagram illustrating a broadband achromatic metasurface waveplate adapted to include a number of antireflective layers, according to an example embodiment;

[0014] FIG. **3**B illustrates optical response characteristics associated with the broadband achromatic metasurface waveplate of FIG. **3**A, according to an example embodiment;

[0015] FIG. **4**A is a block diagram illustrating a broadband achromatic metasurface waveplate adapted to include an antireflective coating, according to an example embodiment;

[0016] FIG. **4**B illustrates optical response characteristics associated with the broadband achromatic metasurface waveplate of FIG. **4**A, according to an example embodiment;

[0017] FIG. **5**A is a block diagram illustrating a broadband achromatic metasurface waveplate adapted to include gradient index elements, according to an example embodiment;

[0018] FIG. **5**B illustrates optical response characteristics associated with the broadband achromatic metasurface waveplate of FIG. **5**A, according to an example embodiment;

[0019] FIG. **6**A is a block diagram illustrating a broadband achromatic metasurface waveplate adapted to include gradient index elements and an antireflective layer, according to an example embodiment;

[0020] FIG. **6**B illustrates optical response characteristics associated with the broadband achromatic metasurface waveplate of FIG. **6**A, according to an example embodiment;

[0021] FIG. **7** is a flowchart illustrating a method of manufacturing a broadband achromatic metasurface waveplate, according to an example embodiment.

DETAILED DESCRIPTION

[0022] Referring now generally to the Figures, described herein are systems and methods of broadband achromatic metasurface waveplates. Waveplates are fundamental optical components that may be used to control optical properties of light such as the polarization state of light. For example, waveplates may be used to generate circularly polarized light, for polarization rotation, and/or for optical isolation. In various embodiments, waveplates are constructed of birefringent materials (e.g., SiO_2, etc.). For example, a quartz waveplate may be used to impart a first phase retardation on light having a first linear polarization orientation and impart a second phase retardation on light having a second linear polarization orientation that is perpendicular to the first linear polarization orientation.

[0023] In some embodiments, display devices such as organic light-emitting diode (OLED) displays utilize waveplates. For example, an OLED display may include a waveplate, such as a quarter-wave plate, to control optical properties of the OLED display such as a reflectance of the OLED display. To continue the example, pairing the quarter-wave plate with the OLED display may reduce a reflectance (e.g., back reflectance from the environment) of the OLED display, thereby increasing the visibility of the OLED display. In various embodiments, display devices, such as an OLED display, may operate over broad bandwidth of light such as light with wavelengths extending over a bandwidth of at least 100 nanometers. Therefore, it may be desirable to utilize broadband waveplates (e.g., waveplates that modify a characteristic of light with wavelengths extending over a bandwidth of at least 100 nanometers, etc.) with display devices such as OLED displays.

[0024] Moreover, in various embodiments, it may be desirable to utilize achromatic waveplates. Achromatic waveplates may limit the effects of chromatic aberration. For example, achromatic waveplates may focus light of a first wavelength (e.g., 450 nanometers, etc.) and light of a second wavelength (e.g., 650 nanometers, etc.) on substantially the same plane, thereby reducing chromatic distortions caused by differentially focused wavelengths. To continue the example, pairing an achromatic waveplate with a display such as an OLED display may reduce/limit chromatic distortion associated with the combined device (e.g., the OLED display paired with a waveplate, etc.), thereby increasing the visibility and/or accuracy of the OLED display (e.g., as compared with an OLED display including a chromatic waveplate, etc.).

[0025] In various embodiments, it is desirable for displays, such as OLED displays, to have high brightness (e.g., luminance). For example, a phone display may have a high brightness to facilitate visibility in high ambient light environments. Therefore, it may be desirable to utilize waveplates having high transmission characteristics. For example, a waveplate having a high transmission rate (e.g., above 90%, etc.) may facilitate passing a large proportion of incident light, thereby reducing environmental reflections and/or limiting dimming a light source such as a display.

[0026] Systems and methods of the present disclosure may address these challenges by presenting a metasurface waveplate that operates over a broad bandwidth of light while maintaining a high transmission rate over the bandwidth of light and limiting distortions (e.g., chromatic distortions, etc.) over the bandwidth of light. Additionally, methods of manufacturing a metasurface waveplate are discussed herein. It should be understood that while the broadband achromatic metasurface waveplate of the present disclosure is described in relation to applications within display technology (e.g., pairing with OLED displays, etc.), other possible applications of the broadband achromatic metasurface waveplate of the present disclosure not explicitly mentioned herein are possible and within the scope of the present disclosure.

[0027] Referring now to FIG. **1**, broadband achromatic metasurface waveplate **100** is shown, according to an example embodiment. Speaking generally, waveplate **100** may modify incident light with wavelengths extending over a broad bandwidth to impart a substantially uniform phase retardation (e.g., $\pi/2$, π, etc.) across the wavelengths while maintaining a high transmittance across the wavelengths (e.g., an average transmittance of at least 90% across the wavelengths, etc.). As used herein, the term "substantially uniform phase retardation" refers to a phase retardation with less than 5% average error across a bandwidth. For example, a substantially uniform phase retardance may refer to a phase retardance that various within a range of 0.08 radians/it. Similarly, as used herein, the term "achromatic" refers to less than 5% average error across a bandwidth. Moreover, as used herein, the term "broad bandwidth" refers to light with wavelengths extending over a bandwidth of at least 100 nanometers. As used herein, the term "high transmittance" refers to an average transmittance of at least 90% across a bandwidth. In various embodiments, waveplate **100** is usable with displays such as OLED displays to increase a visibility of the displays (e.g., by reducing glare, etc.).

[0028] Waveplate **100** is shown to include a number of nanostructures **102** physically coupled to substrate **104**. In various embodiments, waveplate **100** is a metasurface waveplate. Speaking generally, a metasurface is a structure having elements (e.g., nanostructures, nanopillars, nanofins, etc.) that are spaced less than the wavelength of the phenomena (e.g., electromagnetic waves such as light, etc.) that the elements influence apart. For example, a metasurface that operates on light having a wavelength of 600 nanometers may include nanopillars that are spaced 100 nanometers apart. In various embodiments, substrate **104** is constructed of a material having a first refractive index (e.g., n_1) and nanostructures **102** are constructed of a material having a second refractive index (e.g., n_2) that is different than the first refractive index. For example, substrate **104** may be constructed of SiO_2 having a refractive index of ~1.46 across the visible spectrum (e.g., wavelengths in approximately the 450 nanometer to 650 nanometer range, etc.) and nanostructures **102** may be constructed of TiO_2 having a refractive index of ~2.41 across the visible spectrum. In various embodiments, substrate **104** and nanostructures **102** may be constructed of other materials and/or combinations thereof. For example, nanostructures **102** may be constructed of a spatially varying mix of SiO_2 and TiO_2 (e.g., a gradient index such as a radial gradient index, etc.). As another example, substrate **104** and/or nanostructures **102** may be constructed of CaF_2, Si, Fe, ZnS, and/or ZnSe.

[0029] As shown, nanostructures **102** may have a height h, width w, and period p. In various embodiments, waveplate **100** receives incident light **120** having bandwidth **122** and imparts a substantially uniform phase retardation across bandwidth **122** of incident light **120** to produce modified light **130**. In various embodiments, modified light **130** has substantially the same intensity as incident light **120**. For example, modified light **130** may have an intensity that is 95% of that of incident light **120**. In various embodiments, waveplate **100** operates on light with wavelengths extending between 450 nanometers and 650 nanometers. However, it should be understood that waveplate **100** may operate on other wavelengths (e.g., bandwidths, etc.) and that all such embodiments are within the scope of the present disclosure. For example, waveplate **100** may operate on wavelengths extending between 0.8λ and 1.2λ, where λ is a wavelength of interest. In various embodiments, waveplate **100** operates on light in the near-infrared and/or mid-infrared regions. Waveplate **100** may be compact (e.g., substantially ultrathin, etc.) and may exhibit achromaticity at high-incidence angles (e.g., in the presence of high numerical aperture lenses, at angles up to 60°, etc.).

[0030] Speaking generally, waveplate **100** may achieve phase retardance using form birefringence (e.g., rather than material birefringence, etc.). In various embodiments, waveplate **100** exhibits different effective refractive indices for linearly polarized light along x- and y-orientations.

[0031] Referring now to FIG. **2**, optical response characteristics associated with waveplate **100** are shown, according to an example embodiment. First graph **210** illustrates theoretical performance characteristics associated with a model of waveplate **100** and second graph **220** illustrates measured performance characteristics associated with a manufactured version of waveplate **100**. Specifically, first graph **210** includes phase retardation **212** and transmittance **214**. Similarly, second graph **210** includes phase retardation **222**, x-transmittance **224**, and y-transmittance **226**.

[0032] In various embodiments, first graph **210** corresponds to 400 nanometer (nm) propagation through an infinitely extended TiO_2 waveguide array with p=185 nm and w=130 nm. In various embodiments, height h corresponds to a value that achieves a quarter-wave (π/2) phase retardation between incident x- and y-linearly polarized plane waves. It should be understood that while waveplates of the present disclosure are described in terms of quarter-wave plates, other phase retardation values are possible and fully within the scope of the present disclosure. For example, a broadband achromatic half-wave plate may be designed/fabricated using the systems and methods of the present disclosure (e.g., by doubling a thickness of nanostructures **102**, etc.).

[0033] In various embodiments, first graph **210** illustrates a substantially flat phase retardation **212** with less than 5% error. Likewise, transmittance **214** may be near-unity and uniform across the spectral range.

[0034] In various embodiments, non-idealities may degrade the performance of a practical (e.g., real-world, manufactured, etc.) waveplate when compared with an idealized model of a waveplate. For example, second graph **220** illustrates a reduced transmittance (e.g., x-transmittance **224**, y-transmittance **226**, etc.) compared with first graph **210** caused at least in part by Fabry-Perot resonances that form within the practical waveplate. Moreover, a practical waveplate may introduce reflections at the substrate-nanostructure interface as well as the nanostructure-air interface due to impedance mismatches. For example, as shown in second graph **220**, a practical waveplate may suffer from reduced transmittance. As another example, a practical waveplate may exhibit a transmittance that differs for x- and y-polarizations (e.g., x-transmittance **224**, y-transmittance **226**, etc.). Systems and methods of the present disclosure may address these challenges. For example, systems and methods of the present disclosure may present anti-reflective elements that facilitate impedance matching and reduce and/or eliminate the performance degradations discussed above.

[0035] Referring now to FIG. **3**A, waveplate **300** is shown, according to an example embodiment. Waveplate **300** may be similar to waveplate **100**. For example, waveplate **300** may include a number of nanostructures **302** physically coupled to substrate **304**. In various embodiments, waveplate **300** includes first anti-reflective layer **306** and/or second anti-reflective layer **308**. First anti-reflective layer **306** may be constructed of a third material having a third refractive index (n_3) and second anti-reflective layer **308** may be constructed of a fourth material having a fourth refractive index (n_4). For example, first anti-reflective layer **306** may be constructed of Al_2O_3 and second anti-reflective layer **308** may be constructed of SiO_2. In various embodiments, n_3 and/or n_4 are determined according to the formula:

$$n_{AR}=\sqrt{n_1 n_2}$$

where n_{AR} is the refractive index to be determined (e.g., n_3 or n_4, etc.), and n_1 and n_2 are the refractive indices of the adjacent materials (e.g., the material making up substrate

304 and the material making up nanostructures **302** in the case of first anti-reflective layer **306**, etc.). For example, if waveplate **300** is surrounded by air then n_{AR} for second anti-reflective layer **308** may be equal to $\sqrt{n_{Air}n_2}$. However, it should be understood that waveplate **300** may be positioned/integrated within various mediums (e.g., integrated as a layer within a larger device, etc.) and that the choice of anti-reflective material depends upon the surrounding materials. In various embodiments, the materials for first anti-reflective layer **306** and second anti-reflective layer **308** are selected based on the determined refractive indices. For example, n_3 and/or n_4 may be determined as described above and a suitable material may be selected having the determined refractive index values.

[0036] In various embodiments, h_1=390 nm, w=130 nm, p=185 nm, h_2=78 nm, and h_3=95 nm. However, it should be understood that the layout and/or dimensions of waveplate **300** may vary depending on application and that all such variations are within the scope of the present disclosure.

[0037] In various embodiments, the effective indices at 550 nm for transverse electric (TE) wave modes and transverse magnetic (TM) wave modes in waveplate **300** are n_{TE}=1.8467 and n_{TM}=2.1180 respectively. In various embodiments, first anti-reflective layer **306** is a quarter-stack having a refractive index equal to the effective index of the TE mode (e.g., $n_3=n_{TE}$). Additionally or alternatively, second anti-reflective layer **308** may be a quarter-stack having a refractive index equal to the effective index of the TM mode (e.g., $n_4=n_{TM}$). In various embodiments, the inclusion of first anti-reflective layer **306** and/or second anti-reflective layer **308** facilitate mitigating the non-idealities discussed above. For example, first anti-reflective layer **306** and/or second anti-reflective layer **308** may facilitate flattened optical response characteristics and/or increased transmittance (e.g., compared with a waveplate that does not include first anti-reflective layer **306** and/or second anti-reflective layer **308** such as waveplate **100**, etc.) as illustrated below with reference to FIG. 3B.

[0038] Referring now to FIG. 3B, graph **310** illustrates optical response characteristics of waveplate **300**, according to an example embodiment. Similar to first graph **210** and second graph **220**, graph **310** is shown to include phase retardation **312** and transmittance **314**. As shown in graph **310**, waveplate **300** may offer benefits over other systems. For example, waveplate **300** may address at least some of the challenges (e.g., non-idealities, etc.) discussed above. In various embodiments, waveplate **300** exhibits an average transmittance of approximately 97.5%. Moreover, phase retardation **312** and transmittance **314** may be substantially flattened compared with the optical response characteristics of waveplate **100**. In various embodiments, waveplate **300** may be desirable in applications that include applying subsequent material to waveplate **300** (e.g., applying material to second anti-reflective layer **308**, etc.) because waveplate **300** includes a uniform surface that facilitates the application of additional material (e.g., when compared to the non-uniform surface of nanostructures **102**, etc.).

[0039] Referring now to FIG. 4A, waveplate **400** is shown, according to an example embodiment. Waveplate **400** may be similar to waveplate **100**. For example, waveplate **400** may include a number of nanostructures **402** physically coupled to substrate **404**. In various embodiments, waveplate **400** includes anti-reflective film **406**. Anti-reflective film **406** may be applied to a surface of nanostructures **402** and/or substrate **404**. Anti-reflective film **406** may be constructed of a third material having a third refractive index (n_3). For example, anti-reflective film **406** may be constructed of Al_2O_3. In some embodiments, anti-reflective film **406** is constructed of a material having a refractive index determined according to the equation:

$$n_{AR} = \sqrt{\frac{n_{eff,x} + n_{eff,y}}{2} * n_{embedding}}$$

where $n_{eff,\,x}$ is an effective refractive index of nanostructures **402** in the x-direction, $n_{eff,\,y}$ is an effective refractive index of nanostructures **402** in the y-direction, and $n_{embedding}$ is an refractive index of an embedding material (e.g., air, etc.). In various embodiments, anti-reflective film **406** has a uniform thickness (e.g., height, etc.). Anti-reflective film **406** may at least partially reduce reflections at an interface of waveplate **400**, thereby flattening the optical response characteristics of waveplate **400** and/or increasing a transmittance associated with waveplate **400** (e.g., when compared with a waveplate that does not include anti-reflective film **406** such as waveplate **100**, etc.).

[0040] In various embodiments, w=100 nm, h_1=760 nm, p=200 nm, and h_2=40 nm. However, it should be understood that the layout and/or dimensions of waveplate **400** may vary depending on application and that all such variations are within the scope of the present disclosure.

[0041] In various embodiments, the inclusion of anti-reflective film **406** facilitates mitigating the non-idealities discussed above. For example, anti-reflective film **406** may facilitate flattened optical response characteristics and/or increased transmittance (e.g., compared with a waveplate that does not include anti-reflective film **406** such as waveplate **100**, etc.) as illustrated below with reference to FIG. 4B.

[0042] Referring now to FIG. 4B, graph **410** illustrates optical response characteristics of waveplate **400**, according to an example embodiment. Similar to first graph **210** and second graph **220**, graph **410** is shown to include phase retardation **412** and transmittance **414**. As shown in graph **410**, waveplate **400** may offer benefits over other systems. For example, waveplate **400** may address at least some of the challenges (e.g., non-idealities, etc.) discussed above. In various embodiments, waveplate **400** exhibits an average transmittance of 93%. Moreover, phase retardation **412** and transmittance **414** may be substantially flattened compared with the optical response characteristics of waveplate **100**. In various embodiments, waveplate **400** may be desirable in applications that require simplicity in fabrication. For example, waveplate **400** may save a fabrication step compared with the sandwich structure of waveplate **300**.

[0043] Referring now to FIG. 5A, waveplate **500** is shown, according to an example embodiment. Waveplate **500** may be similar to waveplate **100**. For example, waveplate **500** may include a number of nanostructures **502** physically coupled to substrate **504**. Nanostructures **502** may have a spatially-varying refractive index (e.g., a gradient index, etc.). For example, nanostructures **502** may have a gradient index with a Gaussian profile within each of nanostructures **502**. In various embodiments, the refractive index of nanostructures **502** has an x-profile **506** and a y-profile **508**. For example, the refractive index of each of nanostructures **502** may have a spatially-varying profile that resembles a Gaussian distribution in the x-direction (e.g., x-profile **506**) and a bimodal distribution in the y-direction (e.g., y-profile **508**). In various embodiments, the refractive index of nanostructures **502** is highest at a center of each of nanostructures **502** and reduces towards the edges of each of nanostructures **502** (e.g., towards the bottom and sides of each of the nanostructures, etc.). In various embodiments, the spatially-varying refractive index of each of nanostructures **502** is determined according to the formula:

$$n(d) = n_1 + (n_2 - n_1) * e^{\left(\frac{-d}{0.2*0.5w}\right)^2}$$

where d is a distance from the side and bottom (e.g., the interface between nanostructures **502** and substrate **504**) of each of nanostructures **502** to the center of each of nanostructures **502**. In various embodiments, $n_1=1.90$ and $n_2=2.41$. In various embodiments, nanostructures **502** are constructed of a combination of TiO_2 and SiO_2. For example, TiO_2 and SiO_2 may be combined in different ratios to produce a number of amalgams having different refractive indices. In some embodiments, nanostructures **502** are constructed having a continuous gradient of refractive indices. Additionally or alternatively, nanostructures **502** may be constructed with stepwise refractive indices.

[0044] In various embodiments, w=180 nm, p=235 nm, and h=780 nm. However, it should be understood that the layout and/or dimensions of waveplate **500** may vary depending on application and that all such variations are within the scope of the present disclosure.

[0045] In various embodiments, the use of a gradient index in nanostructures **502** facilitates mitigating the non-idealities discussed above. For example, the gradient index may facilitate flattened optical response characteristics and/or increased transmittance (e.g., compared with a waveplate that does not include a gradient index such as waveplate **100**, etc.) as illustrated below with reference to FIG. **5**B.

[0046] Referring now to FIG. **5**B, graph **510** illustrates optical response characteristics of waveplate **500**, according to an example embodiment. Similar to first graph **210** and second graph **220**, graph **510** is shown to include phase retardation **512** and transmittance **514**. As shown in graph **510**, waveplate **500** may offer benefits over other systems. For example, waveplate **500** may address at least some of the challenges (e.g., non-idealities, etc.) discussed above. In various embodiments, waveplate **500** exhibits an average transmittance of 92%. Moreover, phase retardation **512** and transmittance **514** may be substantially flattened compared with the optical response characteristics of waveplate **100**. The gradient index of nanostructures **502** may at least partially reduce reflections Fabry-Perot resonances, thereby flattening the optical response characteristics of waveplate **500** and/or increasing a transmittance associated with waveplate **500** (e.g., when compared with a waveplate that does not include nanostructures **502** having a gradient index such as waveplate **100**, etc.).

[0047] Referring now to FIG. **6**A, waveplate **600** is shown, according to an example embodiment. Waveplate **600** may be similar to waveplate **500**. For example, waveplate **600** may include a number of nanostructures **602** physically coupled to substrate **604**. Additionally, nanostructures **602** may have a spatially-varying refractive index (e.g., a gradient index, etc.). For example, nanostructures **602** may have a gradient index with x-profile **606** and y-profile **608**. In various embodiments, waveplate **600** includes anti-reflective layer **610**. Anti-reflective layer **610** may be constructed of a third material having a third refractive index (n_3). For example, anti-reflective layer **610** may be constructed of Al_2O_3.

[0048] In various embodiments, w=180 nm, p=235 nm, h_1=780 nm, and h_2=90 nm. However, it should be understood that the layout and/or dimensions of waveplate **600** may vary depending on application and that all such variations are within the scope of the present disclosure.

[0049] In various embodiments, the inclusion of anti-reflective layer **610** facilitates mitigating the non-idealities discussed above. For example, anti-reflective layer **610** may facilitate flattened optical response characteristics and/or increased transmittance (e.g., compared with a waveplate that does not include anti-reflective layer **610** such as waveplate **500**, etc.) as illustrated below with reference to FIG. **6**B.

[0050] Referring now to FIG. **6**B, graph **612** illustrates optical response characteristics of waveplate **600**, according to an example embodiment. Similar to first graph **210** and second graph **220**, graph **612** is shown to include phase retardation **614** and transmittance **616**. As shown in graph **612**, waveplate **600** may offer benefits over other systems. For example, waveplate **600** may address at least some of the challenges (e.g., non-idealities, etc.) discussed above. In various embodiments, waveplate **600** exhibits an average transmittance of 99% (e.g., across the 450 nm to 650 nm range). Moreover, phase retardation **614** and transmittance **616** may be substantially flattened compared with the optical response characteristics of waveplate **100**. The gradient index of nanostructures **602** may at least partially reduce reflections Fabry-Perot resonances, thereby flattening the optical response characteristics of waveplate **600** and/or increasing a transmittance associated with waveplate **600** (e.g., when compared with a waveplate that does not include nanostructures **602** having a gradient index such as waveplate **100**, etc.).

[0051] Referring now to FIG. **7**, method **700** of manufacturing a broadband achromatic metasurface waveplate is shown, according to an example embodiment. In various embodiments, method **700** is used to fabricate waveplate **500** and/or waveplate **600**. For example, method **700** may facilitate manufacturing a waveplate having a gradient index profile.

[0052] In various embodiments, method **700** is implemented by a computing system such as a processing circuit having a processor and memory. For example, method **700** may be implemented as non-transitory computer-readable instructions that are executed by a processing circuit to cause the processing circuit to perform the various operations described herein. The operations described herein may be implemented using software, hardware, or a combination thereof. A processing circuit may include a microprocessor, ASIC, FPGA, etc., or combinations thereof. In many embodiments, a processing circuit may include a multi-core processor or an array of processors. Memory may include, but is not limited to, electronic, optical, magnetic, or any other storage devices capable of providing the processor with program instructions. Memory may include a floppy disk, CDROM, DVD, magnetic disk, memory chip, ROM, RAM, EEPROM, EPROM, flash memory, optical media, or any other suitable memory from which the processor can read instructions. The instructions may include code from any suitable computer programming language such as, but not limited to, C, C++, C#, Java, JavaScript, Perl, HTML, XML, Python and Visual Basic.

[0053] At step **710**, a processing circuit may receive a description of a gradient index comprising a number of refractive indices. For example, the processing circuit may receive a computer-aided design (CAD) file describing a waveplate similar to waveplate **500** and including a number of nanostructures each having a spatially-varying refractive index profile (e.g., a gradient index, etc.). In some embodiments, the gradient index is a continuous gradient index (e.g., varying continuously from a center of a nanostructure to an edge of the nanostructure, etc.). Additionally or alternatively, the gradient index may be a stepwise gradient index (e.g., varying in steps from a center of a nanostructure to an edge of the nanostructure, etc.). For example, the gradient index may include 3 steps.

[0054] At step **720**, the processing circuit may determine, according to the description of the gradient index, a number of mixtures comprising (i) a first material having a first refractive index and (ii) a second material having a second refractive index that is different than the first refractive index. For example, step **720** may include combining pre-cursors for TiO_2 and SiO_2 in varying ratios. As another example, step **720** may include combining pre-cursors for TiO_2 and MgF_2 in varying ratios. In various embodiments, each of the number of mixtures is associated with a refractive index of the number of refractive indices of the gradient index. For example, step **720** may include determining a mixture of TiO_2 and SiO_2 that achieves each of the number of refractive indices.

[0055] At step **730**, the processing circuit may apply, using the number of mixtures, a number of film layers on a substrate to achieve the gradient index. For example, step **730** may include combining the pre-cursors of (i) TiO_2 and (ii) at least one of MgF_2 or SiO_2 in varying ratios during each deposition loop of an electronbeam lithography process to achieve the desired gradient index (e.g., via Maxwell-Garnett material mixtures of TiO_2 and SiO_2, etc.). It should be understood that while method **700** is described in relation to TiO_2 and SiO_2, any materials may be used and all such variations are within the scope of the present disclosure. In various embodiments, step **730** includes applying the film layers sequentially (e.g., one on top of another, etc.) while varying the material mixtures within each film layer and between film layers to achieve the desired x- and y-profiles (e.g., x-profile **606** and y-profile **608**, etc.). Additionally or alternatively, step **730** may include fabricating each nanostructure (e.g., such as nanostructures **402**, etc.) and subsequently applying layers around each nanostructure to achieve the gradient index (e.g., via backfill, etc.).

[0056] At step **730**, the metasurface waveplate may be illuminated with light having wavelengths extending over a bandwidth of at least 100 nm. The waveplate may impart a substantially uniform phase retardation across the wavelengths. For example, the waveplate may impart a phase retardation that varies within a range of 0.08 radians/it. Additionally or alternatively, the waveplate may exhibit a transmittance of at least 90% across the wavelengths. In various embodiments, step **730** is optional. In various embodiments, the waveplate is integrated into a device such as a smartphone display. However, it should be understood that the waveplate may be integrated into any device that would benefit from the optical response characteristics of the waveplate and that all such embodiments are within the scope of the present disclosure.

[0057] As used herein, the terms "approximately," "substantially," "substantial" and "about" are used to describe and account for small variations. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation. For example, when used in conjunction with a numerical value, the terms can refer to a range of variation less than or equal to ±10% of that numerical value, such as less than or equal to ±5%, less than or equal to ±4%, less than or equal to ±3%, less than or equal to ±2%, less than or equal to ±1%, less than or equal to ±0.5%, less than or equal to ±0.1%, or less than or equal to ±0.05%. For example, two numerical values can be deemed to be "substantially" the same or equal to each other if a difference between the values is less than or equal to ±10% of an average of the values, such as less than or equal to ±5%, less than or equal to ±4%, less than or equal to ±3%, less than or equal to ±2%, less than or equal to ±1%, less than or equal to ±0.5%, less than or equal to ±0.1%, or less than or equal to ±0.05%.

[0058] While the present disclosure has been described and illustrated with reference to specific embodiments thereof, these descriptions and illustrations do not limit the present disclosure. It should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the true spirit and scope of the present disclosure as defined by the appended claims. The illustrations may not be necessarily drawn to scale. There may be distinctions between the artistic renditions in the present disclosure and the actual apparatus due to manufacturing processes and tolerances. There may be other embodiments of the present disclosure which are not specifically illustrated. The specification and drawings are to be regarded as illustrative rather than restrictive. Modifications may be made to adapt a particular situation, material, composition of matter, method, or process to the objective, spirit and scope of the present disclosure. All such modifications are intended to be within the scope of the claims appended hereto. While the methods disclosed herein have been described with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form an equivalent method without departing from the teachings of the present disclosure. Accordingly, unless specifically indicated herein, the order and grouping of the operations are not limitations of the present disclosure.

What is claimed is:

1. A broadband achromatic metasurface waveplate, comprising:

a device comprising a plurality of nanostructures physically coupled to a substrate and formed at least partially of a dielectric material having a first refractive index; and

an anti-reflective film applied to a surface of the device, the anti-reflective film comprising a material having a second refractive index that is less than the first refractive index; and

wherein the device and the anti-reflective film modify incident light with wavelengths extending over a bandwidth of at least 0.8λ to 1.2λ, to impart a substantially uniform phase retardation across the wavelengths, and a transmittance of at least 90 percent across the wavelengths.

2. The broadband achromatic metasurface waveplate of claim **1**, wherein the second refractive index is substantially equal to the square root of the product of the first refractive index and a third refractive index.

3. The broadband achromatic metasurface waveplate of claim **1**, wherein the wavelengths extend between at least 450 nanometer and 650 nanometer.

4. The broadband achromatic metasurface waveplate of claim **1**, wherein the substantially uniform phase retardation varies within a range of 0.08 radians/π.

5. The broadband achromatic metasurface waveplate of claim **1**, wherein the dielectric material includes TiO_2 and wherein the material includes Al_2O_3.

6. A metasurface waveplate, comprising:

a substrate having a first refractive index;

a plurality of nanostructures coupled to the substrate and formed at least partially of a dielectric material having a second refractive index;

a first anti-reflective film positioned between the substrate and the plurality of nanostructures, the first anti-reflective film having a third refractive index that is greater than the first refractive index and less than the second refractive index; and

a second anti-reflective film positioned at least partially on a surface of the plurality of nanostructures, the second anti-reflective film having a fourth refractive index that is less than the second refractive index; and

wherein the substrate, the plurality of nanostructures, the first anti-reflective film, and the second anti-reflective film modify incident light with wavelengths extending over a bandwidth of at least 0.8λ to 1.2λ to impart a substantially uniform phase retardation across the wavelengths and a transmittance of at least 90 percent across the wavelengths.

7. The metasurface waveplate of claim **6**, wherein the third refractive index is substantially equal to the square root of the product of (i) the first refractive index and (ii) an effective index along a slow axis of a device comprising the substrate and the plurality of nanostructures.

8. The metasurface waveplate of claim **6**, wherein the fourth refractive index is substantially equal to the square root of the product of (i) an effective index along a slow axis of a device comprising the substrate and the plurality of nanostructures and (ii) a fifth refractive index.

9. The metasurface waveplate of claim **6**, wherein the wavelengths extend between at least 450 nanometer and 650 nanometer.

10. The metasurface waveplate of claim **6**, wherein the substantially uniform phase retardation varies within a range of 0.08 radians/π.

11. The metasurface waveplate of claim **6**, wherein the dielectric material includes TiO_2 and wherein the first anti-reflective film includes Al_2O_3.

12. The metasurface waveplate of claim **6**, wherein the dielectric material includes TiO_2 and wherein the second anti-reflective film includes SiO_2.

13. A metasurface waveplate, comprising:

a device comprising a plurality of nanostructures physically coupled to a substrate having a first refractive index, each nanostructure of the plurality of nanostructures having a radial gradient index centered on the nanostructure, wherein the radial gradient index includes an upper refractive index and a lower refractive index, and wherein the upper refractive index is greater than the first refractive index; and

wherein device modifies incident light with wavelengths extending over a bandwidth of at least 0.8λ to 1.2λ to impart a substantially uniform phase retardation across the wavelengths and a transmittance of at least 90 percent across the wavelengths.

14. The metasurface waveplate of claim **13**, wherein the wavelengths extend between at least 450 nanometer and 650 nanometer.

15. The metasurface waveplate of claim **13**, wherein the substantially uniform phase retardation varies within a range of 0.08 radians/π.

16. The metasurface waveplate of claim **13**, further comprising an anti-reflective film applied to a surface of the device, the anti-reflective film comprising a material having a second refractive index that is less than the upper refractive index.

17. The metasurface waveplate of claim **16**, wherein the second refractive index is substantially equal to the square root of the product of (i) a refractive index associated with the plurality of nanostructures and (ii) a third refractive index.

18. The metasurface waveplate of claim **16**, wherein the material includes Al_2O_3.

19. The metasurface waveplate of claim **13**, wherein the radial gradient index comprises a combination of (i) TiO_2 and (ii) at least one of MgF_2 or SiO_2.

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