

SELF-ALIGNED NANO-PILLAR COATINGS AND METHOD OF MANUFACTURING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 63/134,372, entitled “Self-Aligned Nano-Pillar Coatings and Method of Manufacturing” and filed January 6, 2021, which is incorporated herein by reference in its entirety for all purposes.

FIELD OF THE INVENTION

[0002] The present invention generally relates to meta-surface structures and methods of manufacturing thereof.

BACKGROUND

[0003] Wave-front shaping and beam-forming are the procedures in which the spatial amplitude/phase distribution of the free-space propagating light can be tailored in order to create a desired beam pattern (e.g., focal spot, deflection, and holography). The traditional methods, widely used in industry, involve dielectric parabolic mirrors/lenses which are bulky, relatively heavy, and curved. These undesired features stem from the physical mechanism behind conventional optical lenses, which is the enforcement of different optical path lengths to accumulate distinct phase delays. In contrast, meta-surfaces include non-uniform subwavelength scatterers with capability of abrupt control over the reflection/transmission phase ($0-2\pi$) and amplitude (0-1) at the interface. These spatially varying phase shifts over the incident light can be realized by utilizing an array of unit-cells having carefully engineered constituent materials, geometry, orientation, and structural parameters.

[0004] In general, meta-surfaces as artificially structured materials can offer device miniaturization, planar and thin form, high spatial resolution, and opportunity of dense integration into optical devices. In addition, they have the potentials to be used for steering the beam propagation direction, shaping the wave-front of light, and imparting information for applications such as sensing, imaging, light detection, and ranging (e.g. LiDAR).

Although there has been remarkable progress in the design of optical meta-surfaces as a promising replacement for conventional optical elements (e.g., gratings, lenses, holograms, wave-plates, polarizers, and spectral filters), there remain several limitations that have not been adequately addressed including the overall efficiency of the large-scale graded-pattern meta-surfaces. In particular, it may be beneficial to achieve highly efficient beam deflection engineering (e.g., maximizing the diffraction efficiency) in order to transfer the total intensity of the impinging light into a desired deflection angle. This can be considered as the underlying mechanism behind a wide range of optical imaging/sensing devices. Thus, it can have a significant impact on the next-generation of flat-lenses with not only low-cost fabrication, planar form factor, and compactness but also relatively high optical efficiency.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The description will be more fully understood with reference to the following figures and data graphs, which are presented as various embodiment of the disclosure and should not be construed as a complete recitation of the scope of the disclosure, wherein:

[0006] Fig. 1A illustrates an isometric view of a nanostructure including nanogratings with a low-index coating in accordance with an embodiment of the invention.

[0007] Fig. 1B illustrates an isometric view of a nanostructure including nanopillars with a low-index coating in accordance with an embodiment of the invention.

[0008] Fig. 1C illustrates a cross-sectional view of the nanopillars disclosed in connection with Fig. 1B.

[0009] Fig. 1D illustrates an isometric view of a nanostructure including nanogratings with a low-index coating in accordance with an embodiment of the invention.

[0010] Fig. 1E illustrates an isometric view of a nanostructure including nanopillars with a low-index coating in accordance with an embodiment of the invention.

[0011] Fig. 1F illustrates a cross-sectional view of the nanopillars disclosed in connection with Fig. 1E.

[0012] Fig. 1G illustrates an isometric view of a nanostructure including nanogratings with a low-index coating in accordance with an embodiment of the invention.

[0013] Fig. 1H illustrates an isometric view of a nanostructure including nanopillars with a low-index coating in accordance with an embodiment of the invention.

[0014] Fig. 1I illustrates a cross-sectional view of the nanopillars disclosed in connection with Fig. 1H.

[0015] Fig. 2 is a schematic of several cross-sections for the 2D building blocks in accordance with embodiments of the invention.

[0016] Figs. 3A-3C illustrate various different cross-sections of different configurations for high-index nanostructures incorporating low-index coatings in accordance with embodiments of the invention.

[0017] Fig. 4A is a schematic of a cascaded circular waveguide filled by different low-/high-index materials in accordance with an embodiment of the invention.

[0018] Fig. 4B is a two-port transverse equivalent network for the high-index nanopillar with circular cross-section including the multilayer low-index caps described in connection with Fig. 4A.

[0019] Fig. 5 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention.

[0020] Figs. 6A-6D illustrate various plots for the various layers of the top low-index coating and the bottom low-index coating in accordance with various embodiment of the invention.

[0021] Fig. 7 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention.

[0022] Figs. 8A-8H illustrate various plots for the various layers of the top low-index coating and the bottom low-index coating in accordance with various embodiment of the invention.

[0023] Fig. 9 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention.

[0024] Figs. 10A-10F illustrate various plots for the various layers of the top low-index coating and the bottom low-index coating in accordance with various embodiment of the invention.

[0025] Fig. 11 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention.

[0026] Figs. 12A-12H illustrate various plots for the various layers of the top low-index coating 906 and the bottom low-index coating 508 in accordance with various embodiments of the invention.

[0027] Fig. 13A is a schematic of total transmission improvement by incorporating multilayer low-index coatings into high-index meta-array in accordance with an embodiment of the invention.

[0028] Fig. 13B illustrates plots comparing the transmission of a metasurface device with and without the low-index coating (e.g. low-index cap) as described in connection with Fig. 13A.

[0029] Fig. 14A is a schematic overview of a supercell including an array of high-index nanopillars in the presence and absence of the multilayer low-index caps in accordance with an embodiment of the invention.

[0030] Fig. 14B is a demonstration of the trend for the far-field radiation patterns of an optimized finite large-scale bending meta-lens in the absence and presence of one, two, ..., and N caps in accordance with an embodiment of the invention.

[0031] Fig. 15 illustrates two periodic meta-gratings including an array of nanopillars with and without multilayer low-index coatings in accordance with an embodiment of the invention.

[0032] Fig. 16 schematically illustrates a focusing lens with a parabolic phase distribution, which may include nanopillar meta-arrays with and without low-index material coatings in accordance with an embodiment of the invention.

[0033] Figs. 17A-17C illustrate exemplary meta-surface devices in accordance with embodiments of the invention.

[0034] Fig. 18 is a table comparison of the optical performances ($\overline{T}$, $\overline{t}$, $\overline{r}$, σ_T , and σ_t) of the Si nanobar unit-cell which are illustrated in Figs. 17A-17C in the absence and

presence of multilayer self-aligned low-index coatings in accordance with various embodiments of the invention.

[0035] Fig. 19 is a table comparison of the optical performances (T_{+1} , T_0 , and R_0) of Si nanogratings in the presence and absence of multilayer self-aligned low-index coatings for target angles of 5° , 10.5° , 16.11° , 21.6° , and 30° in accordance with various embodiments of the invention.

[0036] Fig. 20 is a table comparison of the optical performances ($\overline{T_{+1}}$, $\overline{R_0}$, and $\overline{T_0}$) of the optimized Si nanogratings in the absence and presence of multilayer self-aligned low-index coatings in accordance with various embodiments of the invention.

SUMMARY OF THE DISCLOSURE

[0037] Many embodiments of the invention include a meta-surface device including a substrate; a pattern of high-index pillars formed on the substrate; and a coating of low-index material in direct contact with the high-index pillars, where the coating of low-index material has a lower refractive index than the high-index pillars. Advantageously, the coating of low-index material may increase the optical efficiency of the meta-surface device. In some embodiments, the coating of low-index material may be a multi-layer low-index material comprising two or more layers of low-index material each having a refractive index lower than the high-index pillars. In some embodiments, the low-index material may be coated above or beneath the high-index pillars. In some embodiments, the coating of low-index material includes one or more transverse dimensions about equal to one or more transverse dimensions of the high index pillars.

[0038] Further, many embodiments of the invention include a meta-surface device including: a substrate; a pattern of high-index pillars formed on the substrate; and a coating of low-index material overlapping with the high-index pillars. The coating of low-index material has a lower refractive index than the high-index pillars.

[0039] In various other embodiments, the pattern of high-index pillars includes silicon, germanium, gallium phosphorus, gallium arsenic, gallium antimony, indium phosphorus, indium arsenic, indium antimony, titanium oxide, silicon nitride, or germanium-antimony-

tellurium, and the coating of low-index material includes aluminum oxide, silicon oxide, magnesium oxide, magnesium fluoride, silicon nitride, or hafnium oxide.

[0040] In still various other embodiments, the high-index pillars are surrounded by a low-index encapsulation material.

[0041] In still various other embodiments, the coating of low-index material includes a multi-layer low-index material.

[0042] In still various other embodiments, the multi-layer low-index material includes two or more layers of low-index material each having a refractive index lower than the high-index pillars.

[0043] In still various other embodiments, the substrate comprises lower refractive index than the refractive index of the high-index pillars.

[0044] In still various other embodiments, the coating of low-refractive index material is located on a side of the high-index pillars opposite to the substrate.

[0045] In still various other embodiments, the coating of low-refractive index material is located between the high-index pillars and the substrate.

[0046] In still various other embodiments, the coating of low-refractive index material is located both on a side of the high-index pillars opposite to the substrate and between the high-index pillars and the substrate.

[0047] In still various other embodiments, the coating of low-refractive index material is conformally coated on the top and side surfaces of the high-index pillars.

[0048] In still various other embodiments, the coating of low-refractive index material is coated only on top surfaces of the high-index pillars.

[0049] In still various other embodiments, the high-index pillars each reside within a plurality of openings in the substrate.

[0050] In still various other embodiments, the low-index coating is conformally coated on the substrate including the plurality of openings.

[0051] In still various other embodiments, portions of the low-index coating are between the substrate and the high-index pillars.

[0052] In still various other embodiments, the coating of low-refractive index material comprises one or more transverse dimensions about equal to one or more transverse dimensions of the high-index pillars.

[0053] In still various other embodiments, the high-index pillars comprise a semiconductor or chalcogenide material and the coating of low-refractive index material comprises a lower index dielectric or oxide.

[0054] In still various other embodiments, the coating of low-refractive index material has a refractive index between 1.46 and 2.1.

[0055] In still various other embodiments, the high-index pillars have a refractive index above 1.8.

[0056] In still various other embodiments, the high-index pillars have a refractive index above 2.5.

[0057] In still various other embodiments, the coating of low-index material is in direct contact with the high-index pillars.

[0058] In still various other embodiments, the coating of low-refractive index material is coated only on top surfaces of the high-index pillars.

[0059] In still various other embodiments, the meta-surface device further includes a low-index encapsulation material, wherein the low-index coating is positioned between the low-index encapsulation material and the high-index pillars.

[0060] In still various other embodiments, the meta-surface device further includes a second low-index coating located between the high-index pillars and the substrate.

[0061] In still various other embodiments, the second low-index coating is a continuous layer coating the substrate directly contacting the high index pillars and the encapsulation media.

[0062] In still various other embodiments, the meta-surface device further includes a low-index encapsulation material positioned between the high-index pillars and the low-index coating.

[0063] In still various other embodiments, the low-index coating is a continuous layer coated over the low-index encapsulation material.

[0064] In still various other embodiments, the meta-surface device further includes a second low-index coating located between the high-index pillars and the substrate.

[0065] In still various other embodiments, the second low-index coating is a continuous layer coating the substrate.

[0066] In still various other embodiments, the low-index coating comprises a first top low-index coating and a second top low-index coating, and wherein the second low-index coating includes a first bottom low-index coating and a second bottom low-index coating.

[0067] In still various other embodiments, the first top low-index coating includes a thickness of 25nm-55nm and the second top low-index coating comprises a thickness of 70nm-35nm.

[0068] In still various other embodiments, the first bottom low-index coating includes a thickness of 160nm-185nm and the second bottom low-index coating includes a thickness of 100nm-135nm.

[0069] In still various other embodiments, the low-index coating further includes a third top low-index coating and a fourth top low-index coating, and the second low-index coating includes a third bottom low-index coating and a fourth bottom low-index coating.

[0070] In still various other embodiments, the coating of low-index material provides anti-reflection properties for the high-index pillars.

[0071] Further, many embodiments of the invention include a method of fabricating a meta-surface device, the method including: providing a substrate; fabricating a pattern of high-index pillars on the substrate; and coating the high-index pillars with a low-index coating using a self-aligning deposition process.

[0072] In various other embodiments, the self-aligning deposition process includes conformally coating the high-index pillars.

[0073] In still various other embodiments, the method further includes depositing a low index encapsulation media over the high-index pillars.

[0074] In still various other embodiments, the low index encapsulation media is deposited before coating the high-index pillars such that the low-index coating is positioned above the low index encapsulation media.

[0075] In still various other embodiments, the low index encapsulation media is deposited after coating the high-index pillars such the low index encapsulation media directly contacts a top surface of the low-index coating and the sidewalls of the high-index pillars.

[0076] In still various other embodiments, the self-aligning deposition process includes depositing a high-index layer and one or more low-index layers on top of the high index layer, etching the high-index layer and the one or more low-index layers leaving the high-index pillars and the low-index coating which forms a cap on the high-index pillars.

[0077] Further, many embodiments of the invention include a method of fabricating a meta-surface device, the method including: providing a substrate, the substrate including a plurality of openings; coating the surface of the substrate, including the inside of the plurality of openings with a low-index coating; and depositing a pattern of high-index pillars within the plurality of openings.

[0078] In various other embodiments, the top surface of the high-index pillars is approximately coplanar with the top surface of the low-index coating.

DETAILED DESCRIPTION

[0079] Previous methods of creating transmission efficiency improvements in meta-surface-based optical systems may include:

- Topology adjustment to support high quality factor (Q-factor) features such as guided-mode resonances or optical bound states in the continuum (BICs). The supported high Q-factor resonance may provide robust control for the light and achieve high transmission level and full phase agility but may include both complicated physical geometry and highly accurate fabrication procedures.
- Vertically cascaded multilayer meta-surfaces (e.g. shared-aperture optical platforms). It has been demonstrated that the integration of several layered meta-surfaces can enhance the transmission efficiency possibly due to the increment of light interaction with high-index materials and experiencing strongly coupled electromagnetic modes. However, in some cases, the horizontally arranged

nanostructures may have less fabrication tolerance due to the possible lateral misalignment between cascaded layers and higher incident-angle sensitivity.

- Multi-part unit-cell meta-surfaces. Incorporating more than a single inclusion in each unit-cell with different geometries or structural parameters may add more degrees of freedom in the design and offer the enhancement of the optical efficiency but this approach may not keep the footprint compactness. The enlargement of unit-cell ($>\lambda/2$) may decrease the angle-of-view and diffraction efficiency at the large target angles.

[0080] All-dielectric meta-surfaces, as advanced optical lenses, may be capable of performing beam steering with wide scanning angles, divergence/convergence, and two- and three-dimensional beam-forming/shaping with characteristics superior to the conventional optics, including subwavelength ultra-thin thickness, a flat and planar form, compatibility with micro-/nano-fabrication methods, and low-cost fabrication due at least partially to advances in nanotechnology and materials science. However, unlike conventional optics, they may not be able to direct light with near-unity efficiency. This may be due to several physical phenomena, such as undesired coupling effects between adjacent unit-cells, imperfect realization of the required phase distribution and inaccessibility to full phase pick up (2π), abrupt phase shift in the neighbor elements, and non-uniformity of transmission amplitude during phase modulation. Embodiments of the invention are compatible with available micro-/nano-fabrication techniques and tolerant to the fabrication imperfections in order to improve the diffraction efficiency of meta-surface based lenses.

[0081] The input impedance of optical meta-platforms may vary over the phase tuning range due to the presence of geometrically-different subwavelength unit-cells. This may create an impedance mismatch between the light source and the optical meta-surface, resulting in light reflection or an inefficient power transfer. As an inevitable phenomenon for the intrinsically narrowband meta-surfaces, tuning the structural parameters of building blocks to achieve a spatial phase modulation may create a non-negligible mismatch. As a consequence, some of the power from the source that illuminates the transmit array meta-surface may be reflected back towards the source (e.g. reflection loss).

[0082] Embodiments of the invention pertain to a multi-layer stack of dielectric materials self-aligned to high-index subwavelength structures, such that the transverse dimensions and texture of the multi-layer stack are proportional and related to the transverse dimensions of the subwavelength structure which may enhance the optical performance of the final device. The incorporation of self-aligned multi-layer low-index coatings into a meta-surface-based platform may be carried out in multiple ways, adjustable based on the situational purposes. In some embodiments, the multi-layer stack includes N -layer low-index dielectric materials wherein the layers include refractive indices of $n_i = 1.46 - 2.1$ and thicknesses of $d_i = 5 \text{ nm} - 300 \text{ nm}$, where $i = 1, 2, \dots, N$.

[0083] Figs. 1A-1I illustrate example nanostructures which include self-aligned nanostructure coatings. Each nanostructures may include multi-layer low-index materials above or beneath the main high-index nanostructures. The multi-layer stack may be placed only on top of the high-index one-dimensional (1D) and two-dimensional (2D) inclusions as described in connection with Figs. 1A-1C. Fig. 1A illustrates an isometric view of a nanostructure including nanogratings with a low-index coating in accordance with an embodiment of the invention. The nanogratings 102a are positioned on a substrate 104. The nanogratings 102a may include a high-index material. The low-index coating 106a may be a cap on the nanogratings 102a. The low-index coating 106a may be multilayer coating. The low-index coating 106a has a lower refractive index than the nanogratings 102a. The nanogratings 102a may be nanobars. The nanogratings 102a may be one dimensional nanogratings. Fig. 1B illustrates an isometric view of a nanostructure including nanopillars with a low-index coating in accordance with an embodiment of the invention. The nanopillars 102b are positioned on a substrate 104. The nanopillars 102b may include a high-index material. The low-index coating 106b may be a cap on the nanopillars 102b. The low-index coating 106b may be multilayer coating. The low-index coating 106b has a lower refractive index than the nanopillars 102b. The nanopillars 102b may include a circular cross-section. The nanopillars 102b may be two dimensional nanopillars. Fig. 1C illustrates a cross-sectional view of the nanopillars 102b disclosed in connection with Fig. 1B.

[0084] In some embodiments, for the nanogratings 102a of Fig. 1A and the nanopillars 102b of Fig. 1B, a method of making self-aligned structures may include depositing a high-index layer and then low index-layers, then etching the high-index layer and the low-index layers such that the low-index coating 106a, 106b and the high-index nanogratings 102a or nanopillars 102b both take on the transverse cross-section of a hard mask. In some embodiments, the high-index layer may be masked off and then an oxidation may be performed. Alternatively, a lift-off process, where an opening is defined in a resist (aligned to the high-index nanogratings 102a or nanopillars 102b, or used in the definition of the high-index nanogratings 102a or nanopillars 102b) and then additional dielectric layers are deposited, then the resist is lifted off.

[0085] The multi-layer stack may be placed on the entire meta-surface's interface (both high-index inclusions and substrate), as described in connection with Figs. 1D-1F. Fig. 1D illustrates an isometric view of a nanostructure including nanogratings with a low-index coating in accordance with an embodiment of the invention. The nanogratings 102a share the features discussed in Fig. 1A and these features will not be repeated in detail. A low-index coating 108a may be conformally deposited on the nanogratings 102a. The low-index coating 108a may be a multi-layer low-index coating. The low-index coating 108a has a lower refractive index than the nanogratings 102a. Fig. 1E illustrates an isometric view of a nanostructure including nanopillars with a low-index coating in accordance with an embodiment of the invention. The nanopillars 102b share the features discussed in Fig. 1B and these features will not be repeated in detail. A low-index coating 108b may be conformally deposited on the nanopillars 102b. The low-index coating 108b may be a multi-layer low-index coating. The low-index coating 108b has a lower refractive index than the nanopillars 102b. Fig. 1F illustrates a cross-sectional view of the nanopillars 102b disclosed in connection with Fig. 1E.

[0086] The multi-layer stack may be placed on a patterned low-index dielectric substrate then filled by a high-index material. The multi-layer low-index coatings are laid beneath the high-index nanostructures as described in connection with Figs. 1G-1I. Fig. 1G illustrates an isometric view of a nanostructure including nanogratings with a low-index coating in accordance with an embodiment of the invention. The nanogratings 102a

may be positioned in voids or holes within the substrate 104. A low-index coating 110a may be conformally deposited in the voids or holes such that the low-index coating 110a is positioned between the substrate 104 and the nanogratings 102a. The low-index coating 110a may be a multi-layer low-index coating. The low-index coating 110a has a lower refractive index than the nanogratings 102a. Fig. 1H illustrates an isometric view of a nanostructure including nanopillars with a low-index coating in accordance with an embodiment of the invention. The nanopillars 102b may be positioned in voids or holes within the substrate 104. A low-index coating 110b may be conformally deposited in the voids or holes such that the low-index coating 110b is positioned between the substrate 104 and the nanopillars 102b. The low-index coating 110b may be a multi-layer low-index coating. The low-index coating 110b has a lower refractive index than the nanopillars 102b. Fig. 1I illustrates a cross-sectional view of the nanopillars 102b disclosed in connection with Fig. 1H.

[0087] In contrast to the low-index coating 108a, 108b of Figs. 1D-1F or the low-index coating 110a, 110b of Figs. 1G-1I, the low-index coating 106a, 106b of Fig. 1A-1C may be etched after the deposition. While a 2D building block may only be demonstrated with a circular cross-section, the nanostructures may include regular/irregular polygonal cross-sections as well.

[0088] The low-index coating enhances the optical efficiency of both 1D grating nanostructures and 2D nanopillars with various patterned cross-sectional shapes without adding any significant fabrication complexity. Fig. 2 illustrates other possible unit-cell cross-sections (e.g., x-y plane) in accordance with various embodiments of the invention. The five illustrated categories include but are not limited to non-polygons 202 (e.g., circle, ellipse, and concentric circles), regular/irregular triangles 204, quadrilateral 206 (e.g., rectangle, square, squircle, and concentric rectangles), N-sided polygons 208 ($N > 4$), and others 210 (cross-, C-, L-shaped). Other cross-sections which are not shown here have been contemplated.

[0089] Also, the disclosed low-index coatings may include any other possible inspired or derivative topologies from the ones elaborated in Fig. 1. Figs. 3A-3C illustrate various different cross-sections of different configurations for high-index nanostructures

incorporating low-index coatings in accordance with embodiments of the invention. The low-index coating 106a,106b described in connection with Fig. 1A-1C can be located beneath or both on top and beneath the high-index nanostructures 102a,102b, as shown in Figs. 3A and 3B. Moreover, Fig. 3C illustrates another closely-related topology to the low-index coating 110a,110b described in connection with Fig. 1G-1I. As illustrated, the low-index coating 110a,110b may be absent from top surface of the substrate 104. The low-index coating 110a,110b may be etched or polished from the surface of the substrate 104 such that the nanopillar 102a or the nanograting 102b is level with the surface of the substrate 104.

[0090] Examples of improvements to optical efficiency produced by the low-index coating may include:

- **Total Transmission Improvement:** The increase of the total transmittance (e.g., the ratio of transmitted intensities in all diffraction harmonics to the intensity of incident beam). This can be achieved by enhancing the transmission amplitude of each individually selected meta-surface unit-cell. Under assumption of low dissipative loss in the optical system (e.g., absence of lossy materials or presence of materials with negligibly small extinction coefficients), this also may result in the reduction of reflection.
- **On-demand Beam Deflection Efficiency Enhancement:** Highly directive meta-array with high gain: The enhancement of beam deflection efficiency (the ratio of the power which is transmitted to a desired diffraction order to the total power of the incident beam) for a single target angle up to $\theta < 30^\circ$. This is attainable due to the possibility of obtaining almost a uniform transmission amplitude for all the individual unit-cells which are included in an optimized meta-grating.
- **Full control over radiation pattern side-lobes:** reduction of undesired diffraction orders: The reduction of specular reflection (e.g., the reflected zero-order diffraction) in a transmissive meta-grating while the transmitted zero-order diffraction may be maintained at a low level.
- **Robust applicability for sophisticated beam-forming/shaping:** Diffraction efficiency improvement over wide angle-of-view: Consistent enhancement of diffraction

efficiency for a broad angle-of-view (e.g., -30° to $+30^\circ$) leading to improvement of functionality for more sophisticated lenses, including holograms with maximum deflection angle of $\theta < 30^\circ$ and focusing lenses with f-number as low as approximately 0.9. Generally, these lenses benefit from multiple meta-gratings (e.g., different arrangement of meta-surfaces) with different diffraction angles. As a result, embodiments of the disclosed design techniques may produce the possibility of simultaneous diffraction efficiency improvement over a wide angle-of-view which may lead to the overall functionality improvement with less dependency on the meta-array arrangements.

Nano-Structure Design and Example Methods of Manufacture

[0091] Embodiments of the invention include a versatile concept for incorporating multi-layer low-index coatings into meta-surface based optical platforms. Each of these embodiments includes high-index nanostructures which can be made of Si, Ge, III-V compound semiconductors (e.g., GaP, GaAs, GaSb, InP, InAs, and InSb), TiO₂, SiN, and germanium-antimony-tellurium (GST), or other high-index materials. These high-index nano-elements may form 1D nanograting or 2D pillars with various kinds of patterned cross-sections, as depicted in Fig. 2. These building blocks with refractive indices higher than 1.8 ($n > 1.8$), and a height in the range of $[\lambda/2 - \lambda]$ may produce robust light manipulation via spatial phase modulation. In some embodiments, the high-index nano-elements may have a refractive index higher than 2.5 ($n > 2.5$). These high-index nano-elements can be fabricated through a deposition process such as a sputtering process, followed by patterning via electron beam-, photo-, and nanoimprint-lithography, followed by etching the deposited high-index films.

[0092] It has been discovered that these high-index nano-elements form meta-surface based platforms which include high-index inclusions. These meta-surface based platforms may be faced with optical efficiency limitations. Without limitation to any particular theory, these restrictions may arise due to the lack of possibility of achieving simultaneous full transmission and phase coverage (e.g., perfect impedance matching for all the unit-cells with variable structural parameters). Various embodiments of the

invention include a layered low-index material including Al_2O_3 , SiO_2 , MgO , MgF_2 , SiN , and HfO_2 . This layered low-index material may be coated onto the high-index nano-elements and may help to add more degrees of freedom in the design procedure and enhance the optical efficiency. The low-index layers may be grown by various deposition processes such as chemical vapor deposition (CVD), atomic layer deposition (ALD), plasma enhanced chemical vapor deposition (PECVD), sputtering, and e-beam/thermal evaporation. The low-index films may each have refractive indices in the range of 1.46-2.1 and thicknesses between 5 nm and 300 nm. In some embodiments, different layers of a multi-layer low-index coating may be made out of different low-index coating materials (e.g., one layer may be made out of Al_2O_3 whereas the other may be made out of SiO_2). In contrast to the low-index coating 108a, 108b discussed in connection with Figs. 1D-1F and the low-index coating 110a, 110b discussed in connection with Figs. 1G-1I, the low-index coating 106a, 106b discussed in connection with Figs. 1A-1C may include a further fabrication step, in which the low-index films are etched after their deposition process but before the high-index nanostructure is defined. The etching may be carried out via developing a photoresist film to define the pattern. Advantageously, this single etch step may then define both the high-index pillar and the associated low-index coatings. The photoresist may eventually be removed by a lift-off technique. To sum up, the fabrication of the proposed self-aligned pillar coatings can be carried out using multiple deposition stages and lithography procedures. These straightforward implementation steps make these nanostructures fabrication-friendly and desirable for dense-integration into optical meta-devices.

Example Physical Mechanism

[0093] An analogy between the nanopillar 102b disclosed in connection with Figs. 1B and 1C in presence of the low-index dielectric cap 106b and a circular waveguide with $N+1$ discontinuities is presented. Fig. 4A is a schematic of a cascaded circular waveguide filled by different low-/high-index materials in accordance with an embodiment of the invention. The cascaded circular waveguide may include nanopillars 102b which may be oriented along z-axis, under illumination of TE-/TM-polarized light. The cascaded circular

waveguide may be filled by the nanopillars 102b coated with the low-index coating 106b formed as a low-index dielectric cap. Fig. 4A shows the diagram of a cascaded waveguide configuration comprises four sections: Section 1 is the high-index-filled waveguide including the nanopillars 102b and Sections 2-4 are filled by low-index materials which may include the low-index coatings 106b. The waveguide cross-section may be identical along the nanostructure so the only discontinuity may be related to the change of the optical constant of materials along the propagation direction (e.g. z-axis). An analysis was performed of the propagation of electromagnetic waves including the magnetic transverse (TM) and electric transverse (TE) modes in the case of isotropic circular waveguides. Fig. 4B is a two-port transverse equivalent network for the high-index nanopillar 102b with circular cross-section including the multilayer low-index caps 106b described in connection with Fig. 4A. The transfer matrix of a unit cell composed of a dielectric layer of thickness d_i , refractive index of n_i , and radius of a for TE/TM waves may be written as follows (under assumption of time harmonic fields of the form $e^{i\omega t}$),

$$[T^{TM/TE}] = \begin{bmatrix} A_{cap/pillar} & B_{cap/pillar} \\ C_{cap/pillar} & D_{cap/pillar} \end{bmatrix} = \begin{bmatrix} \cos(\beta_d d) & iZ_{mn}^{TM/TE} \sin(\beta_d d) \\ \frac{i}{Z_{mn}^{TM/TE}} \sin(\beta_d d) & \cos(\beta_d d) \end{bmatrix}, \quad (1)$$

where $\beta_d = \beta \sqrt{1 - (f_c/f)}$ is the complex propagation constant along the z-axis inside the dielectric-filled circular waveguide and the wave impedances for TE and TM waves are $Z_{mn}^{TM} = \eta \sqrt{1 - (f_c/f)}$ and $Z_{mn}^{TE} = \eta / \sqrt{1 - (f_c/f)}$, respectively, under assumption of an operating frequency larger than the cut-off frequency ($f > f_c$). For TE-polarized modes, the cutoff frequency (f_c) is defined as $(f_c)_{mn} = \chi'_{mn} / 2\pi a \sqrt{\mu\epsilon}$ where a is the radius of circular waveguide and χ'_{mn} indicates the n th zero ($n = 1, 2, 3, \dots$) of the derivative of the Bessel function J_m of the first kind and of order m ($m = 0, 1, 2, 3, \dots$). For the sake of simplicity, we investigated only the propagation modes in this cascaded waveguide, filled with isotropic media. The total ABCD (voltage-current transmission) matrix can be obtained by chaining the ABCD matrices of all the cascaded discontinuities in the corresponding waveguide. ABCD parameters are independent upon the source and load impedances. In order to convert ABCD parameters to scattering (S-)parameters, while the common approach is consideration of TE_{mn}/TM_{mn} mode wave-impedance of an empty waveguide with the

same cross-section for the port reference impedance, free space wave impedance was assumed to be consistent with the underlying physics of the problem which is free-standing high-index nanopillar with multi-layer caps. Therefore, $|S_{21}|$ (ratio of the output transmitted power wave divided by the input incident power wave, transmission coefficient) and $|S_{11}|$ (ratio of the reflected power wave divided by the input incident power wave, reflection coefficient) can be calculated as a function of circular waveguide radius. In case of illumination of a specific TE_{mn}/TM_{mn} mode, since all the interfaces have the same cross-section, no other modes can be excited along the cascaded layers. Thus, adding the multiple low-index layers with carefully optimized thicknesses of d_i and refractive indices of n_i to a high-index layer may help to enrich its functionalities and give it the ability to manipulate light with superior optical characteristics. Examples of the significant contributions of multilayer low-index caps may include:

- Increased transmission amplitude ($|S_{21}|$) for the majority of pillar radii,
- Stabilized transmission amplitude response as a function of pillar radius,
- Increased transmission phase span ($\angle S_{21}$) as a function of pillar radius.

[0094] Without limitation to any particular theory, the aforementioned contributions may be achieved because of adding more degrees of freedom to the building block which may make it possible to achieve broader impedance matching between the source and load impedances. This may be equivalent to the full power transition between two mediums while the phase-delay can be robustly controlled. While the physical mechanism may be analogous to the broadband band-pass filters achieved by cascaded waveguides in mm-wave structures, the goal here is keeping the impedance matching for different pillar radii, instead of particularly broadening the frequency bandwidth. The disclosed method may be a robust way to diminish the reflection loss (e.g. loss of some of the power from the source that illuminate the transmissive optical platform reflect back towards the source). As disclosed below, the aforementioned achievements may specifically help to improve the optical efficiency of high-index pillar meta-surfaces.

Other Embodiments

[0095] While the above disclosure relates to a multi-layer cap that may be present on the nanostructures, the multi-layer structure may also be implemented as continuous layers overlapping the nanostructures. The nanostructures may be the nanopillars 102a or the nanogratings 102b discussed above. Fig. 5 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention. The nanostructure may be nanopillars 102a or nanogratings 102b. A bottom low-index coating 508 may be positioned below the nanostructures 102a, 102b such that the bottom low-index coating 508 is between the substrate 104 and the nanostructure 102a, 102b. The bottom low-index coating 508 may be a continuous and/or unpatterned coating. The bottom low-index coating 508 may be a multilayered low-index coating. The nanostructures 102a, 102b may be covered by an encapsulation media 504. A top low-index coating 506 may be positioned on top of the encapsulation media 504. The top low-index coating 506 may be a continuous and/or unpatterned coating. The top low-index coating 506 may be a multilayered low-index coating.

[0096] Figs. 6A-6D illustrate various plots for the various layers of the top low-index coating 506 and the bottom low-index coating 508 in accordance with various embodiment of the invention. The bottom low-index coating 508 may include two low-index layers. Fig. 6A illustrate a plot of various thicknesses for various implementations of a first low-index layer of the bottom low-index coating 508. Fig. 6B illustrate a plot of various thicknesses for various implementations of a second low-index layer of the bottom low-index coating 508. The top low-index coating 506 may include two low-index layers. Fig. 6C illustrate a plot of various thicknesses for various implementations of a first low-index layer of the top low-index coating 506. Fig. 6D illustrate a plot of various thicknesses for various implementations of a second low-index layer of the top low-index coating 506. For Figs. 6A-6D, the vertical axis represents various thicknesses and the horizontal axis represents various designs. For the horizontal axis, P### indicates a certain pitch of the nanostructures 102a, 102b whereas h### indicates a certain height of the nanostructures 102a, 102b. For example, P360-h550.0 indicates a pitch of 360nm and a height of 550nm for the nanostructures 102a, 102b.

[0097] In some embodiments, the top low-index coating 506 includes a first top low-index coating and a second top low-index coating and the bottom low-index coating 508 includes a first bottom low-index coating and a second bottom low-index coating. Various configurations for thicknesses of each of the coatings may be found in Figs. 6A-6D. In some embodiments, the first top low-index coating comprises a thickness of 25nm-55nm and the second top low-index coating comprises a thickness of 70nm-35nm. In some embodiments, the first bottom low-index coating comprises a thickness of 160nm-185nm and the second bottom low-index coating comprises a thickness of 100nm-135nm.

[0098] In some embodiments, the top low-index coating 506 further includes a third top low-index coating and a fourth top low-index coating, and wherein the bottom low-index coating 508 further includes a third bottom low-index coating and a fourth bottom low-index coating (illustrated in Fig. 7). Various configurations for thicknesses of each of the coatings may be found in Figs. 8A-8H.

[0099] Fig. 7 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention. The features of Fig. 7 are described in connection with Fig. 5 and these descriptions will not be repeated. Figs. 8A-8H illustrate various plots for the various layers of the top low-index coating 506 and the bottom low-index coating 508 in accordance with various embodiment of the invention. The bottom low-index coating 508 may include four low-index layers. Fig. 8A illustrate a plot of various thicknesses for various implementations of a first low-index layer of the bottom low-index coating 508. Fig. 8B illustrate a plot of various thicknesses for various implementations of a second low-index layer of the bottom low-index coating 508. Fig. 8C illustrate a plot of various thicknesses for various implementations of a third low-index layer of the bottom low-index coating 508. Fig. 8D illustrate a plot of various thicknesses for various implementations of a fourth low-index layer of the bottom low-index coating 508.

[00100] The top low-index coating 506 may include four low-index layers. Fig. 8E illustrate a plot of various thicknesses for various implementations of a first low-index layer of the top low-index coating 506. Fig. 8F illustrate a plot of various thicknesses for various implementations of a second low-index layer of the top low-index coating 506. Fig. 8G

illustrate a plot of various thicknesses for various implementations of a third low-index layer of the top low-index coating 506. Fig. 8H illustrate a plot of various thicknesses for various implementations of a fourth low-index layer of the top low-index coating 506. For Figs. 8A-8H, The vertical axis represents various thicknesses and the horizontal axis represents various designs. For the horizontal axis, P### indicates a certain pitch of the nanostructures 102a,102b whereas h### indicates a certain height of the nanostructures 102a,102b. For example, P370-h550.0 indicates a pitch of 370nm and a height of 550nm for the nanostructures 102a,102b.

[00101] Fig. 9 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention. Many of the features of Fig. 9 are described in connection with Fig. 5 and these descriptions will not be repeated. In Fig. 9, the nanostructures 102a,102b may be directly coated with a top low-index coating 906. The top low-index coating 906 may be patterned to form a cap directly on the nanostructures 102a,102b. The encapsulation media 504 may be formed on top of the top low-index coating 906 such that the top low-index coating 906 is positioned between the encapsulation media 504 and the nanostructures 102a,102b while the encapsulation media 504 directly contacts the sidewalls of the nanostructures 102a,102b.

[00102] In some embodiments, the top low-index coating 906 includes a first top low-index coating and a second top low-index coating and the bottom low-index coating 508 includes a first bottom low-index coating, a second bottom low-index coating, a third bottom low-index coating, and a fourth bottom low-index coating. Various configurations for thicknesses of each of the coatings may be found in Figs. 10A-10F.

[00103] Figs. 10A-10F illustrate various plots for the various layers of the top low-index coating 906 and the bottom low-index coating 508 in accordance with various embodiment of the invention. The bottom low-index coating 508 may include four low-index layers. Fig. 10A illustrate a plot of various thicknesses for various implementations of a first low-index layer of the bottom low-index coating 508. Fig. 10B illustrate a plot of various thicknesses for various implementations of a second low-index layer of the bottom low-index coating 508. Fig. 10C illustrate a plot of various thicknesses for various

implementations of a third low-index layer of the bottom low-index coating 508. Fig. 10D illustrate a plot of various thicknesses for various implementations of a fourth low-index layer of the bottom low-index coating 508.

[00104] The top low-index coating 906 may include two low-index layers. Fig. 10E illustrate a plot of various thicknesses for various implementations of a first low-index layer of the top low-index coating 906. Fig. 10F illustrate a plot of various thicknesses for various implementations of a second low-index layer of the top low-index coating 906. For Figs. 10A-10F, the vertical axis represents various thicknesses and the horizontal axis represents various designs. For the horizontal axis, P### indicates a certain pitch of the nanostructures 102a,102b whereas h### indicates a certain height of the nanostructures 102a,102b. For example, P390-h600.0 indicates a pitch of 390nm and a height of 600nm for the nanostructures 102a,102b.

[00105] Fig. 11 illustrates a cross-sectional view of a nanostructure implemented with low-index coatings in accordance with an embodiment of the invention. The features of Fig. 11 are described in connection with Fig. 9 and these descriptions will not be repeated. In some embodiments, the top low-index coating 906 includes a first top low-index coating, a second top low-index coating, a third top low-index coating, and a fourth top low-index coating and the bottom low-index coating 508 includes a first bottom low-index coating, a second bottom low-index coating, a third bottom low-index coating, and a fourth bottom low-index coating. Various configurations for thicknesses of each of the coatings may be found in Figs. 12A-12H.

[00106] Figs. 12A-12H illustrate various plots for the various layers of the top low-index coating 906 and the bottom low-index coating 508 in accordance with various embodiments of the invention. The bottom low-index coating 508 may include four low-index layers. Fig. 12A illustrate a plot of various thicknesses for various implementations of a first low-index layer of the bottom low-index coating 508. Fig. 12B illustrate a plot of various thicknesses for various implementations of a second low-index layer of the bottom low-index coating 508. Fig. 12C illustrate a plot of various thicknesses for various implementations of a third low-index layer of the bottom low-index coating 508. Fig. 12D

illustrate a plot of various thicknesses for various implementations of a fourth low-index layer of the bottom low-index coating 508.

[00107] The top low-index coating 906 may include four low-index layers. Fig. 12E illustrate a plot of various thicknesses for various implementations of a first low-index layer of the top low-index coating 906. Fig. 12F illustrate a plot of various thicknesses for various implementations of a second low-index layer of the top low-index coating 906. Fig. 12G illustrate a plot of various thicknesses for various implementations of a third low-index layer of the top low-index coating 906. Fig. 12H illustrate a plot of various thicknesses for various implementations of a fourth low-index layer of the top low-index coating 906. For Figs. 10A-10H, The vertical axis represents various thicknesses and the horizontal axis represents various designs. For the horizontal axis, P### indicates a certain pitch of the nanostructures 102a,102b whereas h### indicates a certain height of the nanostructures 102a,102b. For example, P390-h600.0 indicates a pitch of 390nm and a height of 600nm for the nanostructures 102a,102b.

[00108] While the embodiments discussed above include a two or four low-index layers for the top low-index coating 506,906 and the bottom low-index coating 508, the top low-index coating 506,906 and the bottom low-index coating 508 may include more or less low-index layers. For example, the top low-index coating 506,906 and the bottom low-index coating 508 may include one layer, two layers, three layers, four layers, five layers, etc. Further, the configurations described in connection with Figs. 5-12 may be used with any of the configurations described in connection with Figs. 1-4. The encapsulation media 504 may be deposited through a non-selective process. In cases where the encapsulation media 504 encapsulates the nanostructures 102a,102b, the encapsulation media 504 may encapsulate the full nanostructures 102a,102b including the low index caps 906 as illustrated in Fig. 9 or Fig. 11.

Discussion of Various Example Improvements***Total Transmission Improvements***

[00109] One of the critical criteria in the design and implementation of transmissive optical lenses is related to their capability in order to successfully transmit the power of illuminated light from the source to the target plane. In the meta-surface based lenses, it may be beneficial for all the individually selected meta-surface building blocks to fully transmit the incident beam with negligibly small reflection. It should be emphasized that in order to accomplish the phase agility from 0 to 2π , meta-lenses may include an array of subwavelength unit-cells with various structural parameters (e.g., diameter, width, length, etc). In general, simultaneous high transmission and full phase-shift may not be easily achieved by a simple unit-cell (e.g. nanopillars without multilayer low-index coatings) since the full phase coverage can be mainly accomplished by experiencing local geometrical resonances. This may cause non-uniformity and fluctuation in the spatial distribution of the amplitude of transmitted light.

[00110] As discussed, the nanopillars without multilayer coatings may be unable to achieve ideal impedance matching for all the necessary physical dimensions. Advantageously, the integration of low-index pillar caps/coatings may alleviate this issue and achieve 2π phase shift easier with less reliance on geometrical resonances.

[00111] Fig. 13A is a schematic of total transmission improvement by incorporating multilayer low-index coatings into high-index meta-array in accordance with an embodiment of the invention. As illustrated, bare nanopillars 1302 may include non-ideal optical characteristics which include both non-uniform wavefront and lower transmittance to the meta-array when compared to nanopillars incorporated multilayer low-index coatings 1304. The optimized meta-array 1304 includes self-aligned pillar coatings which may enhance the total transmission and improve the uniformity of the transmitted wavefront. The bare nanopillars 1302 exhibit both non-uniform wavefront and lower transmittance (e.g. the ratio of transmitted power in all diffraction harmonics to the power of incident beam). The meta-array with incorporated multilayer low-index coatings 1304 may exhibit low dissipative loss in the optical system and negligibly small extinction coefficients for the constituent materials which may advantageously decrease reflection.

Fig. 13B illustrates plots comparing the transmission of a metasurface device with and without the low-index coating (e.g. low-index cap) as described in connection with Fig. 13A. As illustrated, the low-index coating creates greater uniformity of total transmission for various positions.

[00112] Let S^{ij} be the S-parameters of the unit-cell, located at the coordinate of (i, j) , depending on the selected physical dimensions (here, diameters of nanopillars). $|S_{11}^{ij}|$ refers to the power reflected from the unitcell as the specular reflection and back-scattering and $|S_{21}^{ij}|$ represents the ratio of the transmitted power to the incident power. $f(x, y)$ is the complex value of fields (e.g., amplitude and phase) at the interface of meta-surface ($z=0$). Therefore, the total incident power at the place of each unitcell, F_{ij} , is equal to $\iint_{\text{unitcell-area}} f(x, y) dx dy$. The total transmission efficiency can be evaluated through,

$$\text{total transmission efficiency} = \frac{\sum_{ij} F_{ij} |S_{21}^{ij}|^2}{\sum_{ij} F_{ij}} \quad (2)$$

Under the local periodicity assumption, the S-parameters may be utilized which may be calculated through the periodic unit-cell study as function of variable physical dimensions (e.g., diameters). The suggested design schemes provide a robust framework to achieve optimal value for Eq. 2. By using an optimization technique linked with an electromagnetic solver based on Maxwell equations (e.g. rigorous coupled-wave analysis; RCWA), the proper physical dimensions such as periodicity, height of high-index inclusions, and the thicknesses/refractive indices of pillar coating layers can be determined in such a way that the full phase pickup with ultimately high transmission level can be realized for all the studied unit-cells. As a consequence, $|S_{21}^{ij}|$ may be increased and the general optical performance of the generated meta-surface may be beyond the commonly used nanopillars without multilayer coatings/caps.

On-demand Beam Deflection Efficiency Enhancement: Highly Directive Meta-Array with High Gain

[00113] In general, the beam deflection with optical meta-surfaces in the transmission mode may be faced with several challenges, namely

- Deviation from the pre-designed deflection angle,
- Low deflection efficiency (also-called gain for a finite meta-array) especially for high bending angles,
- Large half-power beam-width or full-width at half-maximum of the main far-field pattern lobe,
- Limited directivity.

[00114] These can arise due to several possible imperfections such as coupling between neighboring pixels, imperfect realization of the required phase distribution and inaccessibility to full phase pick up (2π), abrupt phase shift in neighbor elements, and non-uniformity of transmission amplitude during phase modulation. The last one can be considered as the most vital factor in order to obtain the beam deflection with optimal optical efficiency. This along with the subwavelength unit cell ($<\lambda/2$), a reasonable height of high-index inclusion ($<\lambda$), and accessibility to the phase-shift of 0 to 2π may be impediments towards a highly directive meta-array with high gain. Embodiments of the self-aligned pillar coating discussed throughout can ameliorate the previously mentioned artifacts by offering higher and uniform transmission amplitude during phase modulation and providing full phase pickup (2π).

[00115] The optical efficiency may be commonly defined through gain and directivity for a finite meta-array. Directivity is the ratio of radiation intensity in a specific direction to the radiation intensity averaged over all directions. The directivity can be calculated as follows:

$$D(\theta, \phi) = \frac{U(\theta, \phi)}{\frac{1}{4\pi} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} U(\theta, \phi) \sin(\theta) d\theta d\phi}, \quad (3)$$

where $U(\theta, \phi)$ is the radiation intensity at $[\theta, \phi]$. Moreover, the gain refers to the directivity multiplied by meta-array efficiency (e.g. the ratio of the radiated power to the incident

power). As discussed above, The incorporation of multilayer low-index coatings can increase the meta-array efficiency thus the gain can be increased in the optical system in case of the increase in directivity. The reduction in gain and directivity may occur due to non-uniform magnitudes of electromagnetic fields on the meta-surface aperture.

[00116] A generic example of the graded-pattern meta-surface used to deflect the incident beam toward the bending angle of θ is shown in Figs. 14A and 14B in the presence and absence of multi-layer low-index caps/coatings in accordance with an embodiment of the invention. Fig. 14A is a schematic overview of a supercell including an array of high-index nanopillars in the presence and absence of the multilayer low-index caps in accordance with an embodiment of the invention. Fig. 14B is a demonstration of the trend for the far-field radiation patterns of an optimized finite large-scale bending meta-lens in the absence and presence of one, two, ..., and N caps in accordance with an embodiment of the invention. α , β , γ , and δ influence the beam-widths of the transmitted signal. The directivity, gain, half power beam width (HPBW), and/or full width half maximum (FWHM) may be improved step-by-step by adding additional the cap layers.

[00117] Fig. 14A illustrates a low-index coating configuration similar to the low-index coating 106a,106b described in connection with Figs. 1A-1C, the beneficial results may be obtained by other low-index coatings described herein as well (e.g. the low-index coating 108a,108b of Figs. 1D-1F or the low-index coating 110a,110b of Figs. 1G-1I). By optimizing the physical parameters of the low-index coating 106a,106b, the optical efficiency of the desired diffraction order (the transmitted first-order diffraction, T_{+1}), correlated to the target bending angle, may be increased. The optimized multi-layer low-index coatings may produce the largest possible value for the deflection efficiency at the single pre-defined bending angle (for instance, $<30^\circ$).

[00118] As schematically illustrated in Fig. 14B, there is a trade-off between the gain/directivity and the beam-width. Increased number of caps may increase the gain and directivity and the beam-width of the far-field radiation pattern main lobe which becomes narrower ($\alpha > \beta > \gamma > \delta$). As a result, the gain, directivity, and HPBW may be increased step-by-step by adding cap layers.

[00119] In comparison with the low-index coating 108a,108b of Figs. 1D-1F or the low-index coating 110a,110b of Figs. 1G-1I, the low-index coating 106a,106b described in connection with Figs. 1A-1C may not be limited to its benefits for the optical efficiency improvement. The low-index coating 106a,106b described in connection with Figs. 1A-1C can also offer the following benefits:

- If one of the incorporated low-index caps has a dissipative loss, the low-index coating 106a,106b described in connection with Figs. 1A-1C can still enable all the aforementioned efficiency improvements. The light interaction with the lossy low-index layer 106a,106b may be limited in contrast to the low-index coating 108a,108b of Figs. 1D-1F or the low-index coating 110a,110b of Figs. 1G-1I.
- The low-index coating 106a,106b described in connection with Figs. 1A-1C can be utilized to improve the optical efficiency of an already fabricated meta-surface with bare high-index nano-pillars. This is also possible in the low-index coating 108a,108b of Figs. 1D-1F. In other words, if a meta-surface has already been fabricated, it may not be necessary to repeat all the fabrication steps again. A single step of deposition of continuous or discrete multi-layer coatings as illustrated in Figs. 1A-1C and Figs. 1D-1F may be utilized in order to improve the impedance matching and increase the optical efficiency.

Full Control Over Radiation Pattern Side-Lobes: Decrease of Undesired Diffraction Orders

[00120] In optical applications involving the light manipulation toward a specific direction, the optical device may benefit from avoidance of the excitation of undesired radiation pattern side-lobes in order to attain optimal functionality. The far-field radiation pattern side-lobes of a finite large-scale meta-lens may be proportional to the excitation of undesired diffraction orders when the meta-lens is studied in the infinitely large periodic fashion. Therefore, the reduction of side-lobes in the finite large-scale meta-lens may be obtained by diminishing the undesired diffraction excitations in periodic meta-gratings. Fig. 15 is a schematic illustration of deduction of the undesired diffraction orders by incorporating multilayer low-index coatings into a high-index meta-array in accordance

with an embodiment of the invention. Fig. 15 illustrates two periodic meta-gratings including an array of nanopillars with and without multilayer low-index coatings in accordance with an embodiment of the invention. Among the undesired diffraction orders, the reflected zero-order (also called specular reflection or mirror-like reflection), the transmitted zero-order (T_0), and transmitted second-order ($T_{\pm 2}$) may be of particular importance since these diffraction orders potentially cause undesired artifacts in imaging and sensing applications through the degradation of image quality or inaccuracy in the light detection for the integrated sensors.

[00121] The incorporation of multi-layer low-index coatings on an array of high-index nanopillars can increase the diffracted power toward the desired angle (e.g. T_{+1}), as discussed above. Based on the conservation of energy in an optical system and upon the absence of dissipative loss (or negligibly small loss), this can be translated to a general degradation of the power which may be transferred to other transmitted/reflected diffraction orders. In addition, we have mentioned above that the total transmission (e.g. the ratio of transmitted power in all diffraction harmonics to the power of the incident beam) may be increased in presence of multilayer low-index coatings. Therefore, this also confirms the overall suppression of the reflected diffraction orders. To sum up, the incorporation of multi-layer low index coatings may help to address and alleviate the concerns regarding the reflected diffraction orders in particular the specular reflection (R_0) as schematically shown in Fig. 15. The trend of the transmitted/reflected diffraction orders is elaborated through the arrows, in which the length of arrows indicates the strength of the corresponding diffraction order. The desired T_{+1} is increased and the undesired diffraction orders (e.g., R_0 , T_0 , and T_{+2}) are decreased or kept small. Furthermore, it can decrease the transmitted higher-order diffractions ($T_{\pm 2}$, $T_{\pm 3}$, ...). Regarding the transmitted zero-order diffraction, its level usually benefits from the periodicity of the unit-cell and realization of the phase distribution at the metagrating interface. Since structures including the multilayer low-index coatings may retain the periodicity and the phase distribution, the transmitted zero-order diffraction level can still be kept relatively small.

Robust Applicability for Sophisticated Beam-Forming/Shaping: Diffraction Efficiency Improvement Over Wide Angle-of-View

[00122] In previous sections, we focused on the optical platforms with beam deflection toward a single bending angle and how multilayer low-index coatings may improve the optical efficiency under various mechanisms including topology optimization. While the capability to improve beam steering toward a specific angle may be beneficial in different optical applications, consistent enhancement of the diffraction efficiency for a broad field-of-view may also be of importance. Functionality improvement for more sophisticated lenses, including the holograms and focusing/convergence lenses may benefit from a broad field-of-view. For example, a focusing lens with a parabolic phase distribution consists of different arrangements of the unit-cells. A first-principles simulation may include solving the electromagnetic fields of an extremely large finite meta-surface which may be computationally expensive and may be repeated case-by-case (e.g. focusing lenses with different focal lengths).

[00123] Fig. 16 schematically illustrates a focusing lens with a parabolic phase distribution, which may include nanopillar meta-arrays with and without low-index material coatings in accordance with an embodiment of the invention. The multilayer low-index coatings may increase the optical efficiency for the focusing functionality. The trend of focusing characteristics is elaborated in which the intensity of the focal point, HPBW, and the spatial position of formed focal point are improved. It may be possible to divide the parabolic phase distribution to several linear phase profiles, which can be fulfilled by supercells similar to the ones discussed in previous sections. The focusing lenses face may have several issues including poor focusing efficiency, large half-power beam-width (HPBW) of the focal spot, deviation from the pre-designed focal length, and large depth of focus (DOF). In a meta-array equipped with multilayer low-index coatings, each supercell can manipulate the light more efficiently thus the focal efficiency may be increased. As a consequence, relatively smaller HPBW and DOF may be achieved when compared to the case in the absence of the multilayer low-index coatings. Designs with the low-index coating may be superior when compared to those without multilayer low-index coatings. By optimization of physical parameters of the design scheme, the overall

structure may be optimized. In some embodiments, designs implementing multilayer low-index coatings may be incorporated in holograms with maximum deflection angle of $\theta < 30^\circ$ and focusing lenses with f-number as low as approximately 0.9.

[00124] Further, the proposed design schemes may include a specific type of high-index materials (e.g. active materials). In some embodiments the high-index materials may be germanium-antimony-telluride (GST, or GeSbTe) and liquid crystals (e.g., E7). These materials may play a central role in active beam-forming/shaping, which may be the fundamental principle behind light detection and ranging devices (LiDAR) used in various applications including autonomous drones/vehicles and wireless/satellite communication nano-/micro-antennas. Therefore, incorporating the multilayer low-index coatings into such optical meta-devices may help to achieve highly-efficient tunable beam-forming/shaping. In particular, the possibility to improve gain, directivity, HPBW, and side-lobe levels may be beneficial for free-space optical communications. In addition, it can help to improve the accuracy of LiDAR devices in capturing the information from the surrounding areas.

Further Sample Embodiments

[00125] Exemplary embodiments are provided to illustrate specific contemplated designs but are in no way limiting. Figs. 17A-17C illustrate exemplary meta-surface devices in accordance with embodiments of the invention each including a high-index material which includes an array of subwavelength Si nanobars ($n_{Si} = 3.789$) with width, height, and periodicity of w , h , and P , surrounded by a low-index material with refractive index of $n_{Encapsulation} = 1.47$ and placed on a low-index substrate with refractive index of $n_{Substrate} = 1.451$. In Figs. 17A-17C, subwavelength Si nano-pillar ($n_{Si} = 3.789$) with height, periodicity, and width of h , P , and w , are embedded into a low-index material with refractive index of $n_{Encapsulation} = 1.47$ and placed on a low-index substrate with refractive index of $n_{Substrate} = 1.451$, in the (left) absence of multi-layer pillar coatings, (middle and right) presence of one and two-layer(s) caps. The illustrated designs of Figs. 17A-17C are those of Figs. 1A-1C which incorporate the self-aligned pillar coatings. Fig. 17A illustrates a high-index nanopillar without the low-index coating. The nanopillar 102b is

encased in an encapsulation media 504. Fig. 17B illustrates the nanopillar 102b with a single layer low index coating 1702. Fig. 17C illustrates the nanopillar 102b with a two layer low index coating 1704.

[00126] Several quantitative criteria may be used to compare the optical performance of Si nanogratings in the presence (Figs. 17B and 17C) and absence (Fig. 17A) of multilayer self-aligned low-index coatings,

- Average of transmittance ($\bar{t}$) or transmission ($\bar{T}$): This may be calculated through dividing the sum total of transmittance/transmission values for different physical dimensions (e.g. widths (w)) by the number of studied width samples (N_w), which may be used for 2π phase-coverage,

$$\bar{t} = \frac{1}{N_w} \sum_{i=1}^{i=N_w} |T(w_i)|^2 = \frac{1}{N_w} \sum_{i=1}^{i=N_w} t(w_i), \quad (4)$$

$$\bar{T} = \frac{1}{N_w} \sum_{i=1}^{i=N_w} |T(w_i)|. \quad (5)$$

- Average of reflectance ($\bar{r}$) or reflection ($\bar{R}$): The average of the reflectance/reflection values calculated for different physical dimensions (e.g. w) over the studied number of width samples (N_w),

$$\bar{r} = \frac{1}{N_w} \sum_{i=1}^{i=N_w} |R(w_i)|^2 = \frac{1}{N_w} \sum_{i=1}^{i=N_w} r(w_i), \quad (6)$$

$$\bar{R} = \frac{1}{N_w} \sum_{i=1}^{i=N_w} |R(w_i)|. \quad (7)$$

- Standard deviation of transmission (σ_T) or transmittance (σ_t): σ_t / σ_T is a measure of how spread out the transmittance/transmission values are. Therefore, it can help to quantify the uniformity of the transmittance/transmission response,

$$\sigma_T = \sqrt{\frac{1}{N_w} \sum_{i=1}^{i=N_w} (|T(w_i)| - \bar{T})^2}, \quad (8)$$

$$\sigma_t = \sqrt{\frac{1}{N_w} \sum_{i=1}^{i=N_w} (t(w_i) - \bar{t})^2}. \quad (9)$$

- Transmitted first-order diffraction (T_{+1}): This is related to the diffracted power toward the desired angle. This can be translated to the increment of directivity ($D(\theta, \varphi)$). In case of increment of meta-array efficiency (e.g. the ratio of the radiated power to the incident power), gain may be increased as well.
- Reflected zero-order diffraction (also called specular reflection or mirror-like reflection, R_0) and the transmitted zero-order diffraction (T_0): These can be considered as undesired diffraction orders which should be diminished in order to decrease the imaging/sensing artifacts. This can be translated to the decrement of the radiation pattern side-lobes in a finite meta-array.
- Average of transmitted first-order diffraction ($\overline{T_{+1}}$), transmitted zero-order diffraction ($\overline{T_0}$), and reflected zero-order diffraction ($\overline{R_0}$): These can be obtained by calculating the average of T_{+1} , T_0 , and R_0 across different target angles (e.g. 5° , 7.7° , 10.5° , 13.3° , 16.11° , 18.8° , 21.6° , 24.4° , 27.2° , and 30°).

Example 1

[00127] Fig. 18 is a table comparison of the optical performances ($\bar{T}$, $\bar{t}$, $\bar{r}$, σ_T , and σ_t) of the Si nanobar unit-cell which are illustrated in Figs. 17A-17C in the absence and presence of multilayer self-aligned low-index coatings in accordance with various embodiments of the invention. The table compares optical performance quantitative values for $\bar{T}$, $\bar{t}$, $\bar{r}$, σ_T , and σ_t obtained from many exemplary embodiments including Si nanogratings in the presence and absence of multilayer self-aligned low-index coatings. The optimized thicknesses (h_{cap}^1 , h_{cap}^2) and refractive indices (n_{cap}^1 , n_{cap}^2) of the multilayer self-aligned coatings are also provided in Fig. 18 along with the height and periodicity of

the Si nanobars (h and P). The width range is considered between 120 nm and (P -120 nm) with the step size of 2 nm.

[00128] As seen, the incorporation of pillar caps helps increase the average of transmission and transmittance ($\bar{T}$ and $\bar{t}$) and decrease the average of reflection and reflectance ($\bar{R}$ and $\bar{r}$). This means higher total transmission in case of presence of multilayer low-index self-aligned coatings. Moreover, the standard deviation of transmittance/transmission (σ_t and σ_T) is decreased by adding the low-index caps which can be translated to a more uniform transmission amplitude during phase modulation for all the individual unit-cells. As a result, the engineered wave-front in the transmission mode will be more uniform. Better performance results were yielded with a higher number of cap/coating layers.

Example 2

[00129] Fig. 19 is a table comparison of the optical performances (T_{+1} , T_0 , and R_0) of Si nanogratings in the presence and absence of multilayer self-aligned low-index coatings for target angles of 5° , 10.5° , 16.11° , 21.6° , and 30° in accordance with various embodiments of the invention. The table compares the transmitted first-order (T_{+1}), transmitted zero-order (T_0), and reflected zero-order (R_0) diffractions of exemplary embodiments including a Si nanograting in the presence and absence of multi-layer self-aligned low-index coatings. The optimized thicknesses (h_{cap}^1 , h_{cap}^2) and refractive indices (n_{cap}^1 , n_{cap}^2) of multilayer self-aligned coatings are also provided in Fig. 11 along with the height and periodicity of Si nanogratings (h and P). The target angles are chosen between $\pi/6$ and $\pi/3$ and the pillar's width range is considered between 120 nm and P -120nm with the step size of 2 nm.

[00130] As indicated in Fig. 19, the integration of self-aligned pillar caps gradually improves the transmitted first-order diffraction (T_{+1}) for almost all the target angles smaller than $\pm 30^\circ$. The results related to the negative target angles are omitted here for the sake of brevity. As illustrated, the values the angles of T_{+1} are more than 5% higher when comparing cases where the low-index coating(s) are present than in the absence of the low-index coating for angles between 5° and 30° . Advantageously, the two-layer low-

index coating is more than 10% higher for the higher target angles (e.g. 30°). Thus, using multi-layer pillar coatings may lead to the implementation of a highly directive meta-array with high gain.

[00131] Furthermore, the reflected zero-order diffraction significantly decreases for the illustrated angles of 5°, 10.5°, 16.11°, 21.6°, and 30°. As illustrated, the reflected zero-order diffractions (R_0) have been decreased at least by 80% of their values for all angles when comparing cases where a two-layer low-index coating is present and where the low-index coating is absent. The transmitted zero-order (T_0) is maintained at a low level for cases where the low-index coating(s) is present or absent. While the values of transmitted/reflected higher-order diffractions, like $T_{\pm 2}$, are not provided, their magnitudes may also be decreased and/or kept negligibly small in presence of multi-layer low-index pillar coatings. Since the enhancement of the optical performance has been obtained in a broad angle-of-view, the presence of multi-layer low index pillar coatings may increase optical efficiency for more sophisticated optical platforms like holograms with maximum deflection angle of $\theta < 30^\circ$ and focusing lenses with f-number as low as approximately 0.9.

[00132] Further, Fig. 20 is a table comparison of the optical performances ($\overline{T_{+1}}$, $\overline{R_0}$, and $\overline{T_0}$) of the optimized Si nanogratings in the absence and presence of multilayer self-aligned low-index coatings in accordance with various embodiments of the invention. Fig. 20 is a table illustrating the results of the self-aligned pillar caps described in connection with Fig. 19 indicating performance criteria for the average of transmitted first-order diffraction ($\overline{T_{+1}}$), transmitted zero-order diffraction ($\overline{T_0}$), and reflected zero-order diffraction ($\overline{R_0}$). It can be clearly seen that the $\overline{T_{+1}}$ increases from 74.84% in the absence of pillar coatings to 80.84% in presence of a single-layer low-index coating and finally became 84.20% by using two-layer self-aligned pillar coatings. Moreover, almost an 85% reduction of the average specular reflection ($\overline{R_0}$) is observed when comparing the absence of pillar coatings and the presence of a two-layer low-index coating. Finally, $\overline{T_0}$ has been decreased from 0.87% in the absence of pillar coatings to 0.68% in the

presence of a two-layer low-index pillar coating. Thus, a skilled artisan would recognize an upward trend of better performance based on more layers of low-index pillar coatings.

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[00133] While the above description contains many specific embodiments of the invention, these should not be construed as limitations on the scope of the invention, but rather as an example of one embodiment thereof. It is therefore to be understood that the present invention may be practiced in ways other than specifically described, without departing from the scope and spirit of the present invention. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive. Accordingly, the scope of the invention should be determined not by the embodiments illustrated, but by the appended claims and their equivalents.

WHAT IS CLAIMED IS:

1. A meta-surface device comprising:
a substrate;
a pattern of high-index pillars formed on the substrate; and
a coating of low-index material overlapping with the high-index pillars, wherein the coating of low-index material has a lower refractive index than the high-index pillars.
2. The meta-surface device of claim 1,
wherein the pattern of high-index pillars comprises silicon, germanium, gallium phosphorus, gallium arsenic, gallium antimony, indium phosphorus, indium arsenic, indium antimony, titanium oxide, silicon nitride, or germanium-antimony-tellurium; and
wherein the coating of low-index material comprises aluminum oxide, silicon oxide, magnesium oxide, magnesium fluoride, silicon nitride, or hafnium oxide.
3. The meta-surface device of claim 1, wherein the high-index pillars are surrounded by a low-index encapsulation material.
4. The meta-surface device of claim 1, wherein the coating of low-index material comprises a multi-layer low-index material.
5. The meta-surface device of claim 4, wherein the multi-layer low-index material comprises two or more layers of low-index material each having a refractive index lower than the high-index pillars.
6. The meta-surface device of claim 1, wherein the substrate comprises lower refractive index than the refractive index of the high-index pillars.
7. The meta-surface device of claim 1, wherein the coating of low-refractive index material is located on a side of the high-index pillars opposite to the substrate.

8. The meta-surface device of claim 1, wherein the coating of low-refractive index material is located between the high-index pillars and the substrate.
9. The meta-surface device of claim 1, wherein the coating of low-refractive index material is located both on a side of the high-index pillars opposite to the substrate and between the high-index pillars and the substrate.
10. The meta-surface device of claim 1, wherein the coating of low-refractive index material is conformally coated on the top and side surfaces of the high-index pillars.
11. The meta-surface device of claim 1, wherein the coating of low-refractive index material is coated only on top surfaces of the high-index pillars.
12. The meta-surface device of claim 1, wherein the high-index pillars each reside within a plurality of openings in the substrate.
13. The meta-surface device of claim 12, wherein the low-index coating is conformally coated on the substrate including the plurality of openings.
14. The meta-surface device of claim 13, wherein portions of the low-index coating are between the substrate and the high-index pillars.
15. The meta-surface device of claim 1, wherein the coating of low-refractive index material comprises one or more transverse dimensions about equal to one or more transverse dimensions of the high-index pillars.
16. The meta-surface device of claim 1, wherein the high-index pillars comprise a semiconductor or chalcogenide material and the coating of low-refractive index material comprises a lower index dielectric or oxide.

17. The meta-surface device of claim 1, wherein the coating of low-refractive index material has a refractive index between 1.46 and 2.1.
18. The meta-surface device of claim 17, wherein the high-index pillars have a refractive index above 1.8.
19. The meta-surface device of claim 18, wherein the high-index pillars have a refractive index above 2.5.
20. The meta-surface device of claim 1, wherein the coating of low-index material is in direct contact with the high-index pillars.
21. The meta-surface device of claim 20, wherein the coating of low-refractive index material is coated only on top surfaces of the high-index pillars.
22. The meta-surface device of claim 21, further comprising a low-index encapsulation material, wherein the low-index coating is positioned between the low-index encapsulation material and the high-index pillars.
23. The meta-surface device of claim 22, further comprising a second low-index coating located between the high-index pillars and the substrate.
24. The meta-surface device of claim 23, wherein the second low-index coating is a continuous layer coating the substrate directly contacting the high index pillars and the encapsulation media.
25. The meta-surface device of claim 1, further comprising a low-index encapsulation material positioned between the high-index pillars and the low-index coating.

26. The meta-surface device of claim 25, wherein the low-index coating is a continuous layer coated over the low-index encapsulation material.
27. The meta-surface device of claim 25, further comprising a second low-index coating located between the high-index pillars and the substrate.
28. The meta-surface device of claim 27, wherein the second low-index coating is a continuous layer coating the substrate.
29. The meta-surface device of claim 28, wherein the low-index coating comprises a first top low-index coating and a second top low-index coating, and wherein the second low-index coating comprises a first bottom low-index coating and a second bottom low-index coating.
30. The meta-surface device of claim 29, wherein the first top low-index coating comprises a thickness of 25nm-55nm and the second top low-index coating comprises a thickness of 70nm-35nm.
31. The meta-surface device of claim 30, wherein the first bottom low-index coating comprises a thickness of 160nm-185nm and the second bottom low-index coating comprises a thickness of 100nm-135nm.
32. The meta-surface device of claim 29, wherein the low-index coating further comprises a third top low-index coating and a fourth top low-index coating, and wherein the second low-index coating comprises a third bottom low-index coating and a fourth bottom low-index coating.
33. The meta-surface device of claim 1, wherein the coating of low-index material provides anti-reflection properties for the high-index pillars.

34. A method of fabricating a meta-surface device, the method comprising:
providing a substrate;
fabricating a pattern of high-index pillars on the substrate; and
coating the high-index pillars with a low-index coating using a self-aligning deposition process.
35. The method of claim 34, wherein the self-aligning deposition process comprises conformally coating the high-index pillars.
36. The method of claim 34, further comprising depositing a low index encapsulation media over the high-index pillars.
37. The method of claim 36, wherein the low index encapsulation media is deposited before coating the high-index pillars such that the low-index coating is positioned above the low index encapsulation media.
38. The method of claim 37, wherein the low index encapsulation media is deposited after coating the high-index pillars such the low index encapsulation media directly contacts a top surface of the low-index coating and the sidewalls of the high-index pillars.
39. The method of claim 34, wherein the self-aligning deposition process comprises depositing a high-index layer and one or more low-index layers on top of the high index layer, etching the high-index layer and the one or more low-index layers leaving the high-index pillars and the low-index coating which forms a cap on the high-index pillars.
40. A method of fabricating a meta-surface device, the method comprising:
providing a substrate, wherein the substrate comprises a plurality of openings;
coating the surface of the substrate, including the inside of the plurality of openings with a low-index coating; and
depositing a pattern of high-index pillars within the plurality of openings.

41. The method of claim 40, wherein the top surface of the high-index pillars is approximately coplanar with the top surface of the low-index coating.