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(71) Applicant: **INTERDIGITAL CE PATENT HOLDINGS, SAS** [FR/FR]; 3 Rue du Colonel Moll, 75017 Paris (FR).(72) Inventors: **VARGHESE, Bobin**; c/o InterDigital 975 Avenue des Champs Blancs, 35576 Cesson-Sévigné (FR). **SHRAMKOVA, Oksana**; c/o InterDigital 975 Avenue des Champs Blancs, 35576 Cesson-Sévigné (FR). **BLONDE, Laurent**; c/o InterDigital 975 Avenue des Champs Blancs, 35576 Cesson-Sévigné (FR). **DRAZIC, Valter**; c/o In-

terDigital 975 Avenue des Champs Blancs, 35576 Cesson-Sévigné (FR).

(74) Agent: **AWA SWEDEN AB**; Box 5117, 200 71 Malmö (SE).

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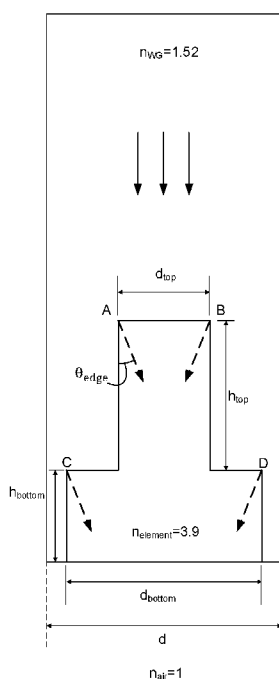


FIG. 13

(57) Abstract: In example embodiments, a reflective diffraction grating system includes a transparent medium having a first refractive index n_{WG} and an outer surface. A periodic array of grating elements is arranged in the transparent medium. The elements have a second refractive index $n_{element}$ that is greater than the first refractive index. The grating elements include an outer region along the outer surface, where the outer region is substantially rectangular in cross-section and has a first width d_{bottom} . The grating elements also include an inner region extending inward from the outer region, where the inner region is substantially rectangular in cross-section and has a second width d_{top} smaller than the first width. The grating elements may be symmetrical in cross-section.

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REFLECTIVE IN-COUPLER DESIGN WITH HIGH REFRACTIVE INDEX ELEMENT USING SECOND DIFFRACTION ORDER FOR NEAR-EYE DISPLAYS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority of EP 20305761.7, entitled “REFLECTIVE IN-COUPLER DESIGN WITH HIGH REFRACTIVE INDEX ELEMENT USING SECOND DIFFRACTION ORDER FOR NEAR-EYE DISPLAYS,” filed 6 July 2020, which is hereby incorporated by reference in its entirety.

BACKGROUND

[0002] The present disclosure is related to the field of optics and photonics and more specifically to the domain of augmented reality (AR) near-eye displays (NED). An AR NED is a form of advanced display technology that can potentially reshape existing ways of performing tasks by allowing its user to visualize virtual images/information superimposed onto the real-world environment simultaneously thereby enhancing the user's view of the real world. Its applications are numerous including in navigation, military, medicine, entertainment and education to name a few.

[0003] This section is intended to introduce the reader to various aspects of art, which may be related to various aspects of the present disclosure that are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the systems and methods described herein. Accordingly, it should be understood that these statements are to be read in this light, and not as admissions of prior art.

[0004] Development of AR/VR glasses (and more generally eyewear electronic devices) is associated with a number of challenges, including reduction of size and weight of such devices as well as improvement of the image quality (in terms of contrast, field of view, color depth, etc.) that should be realistic enough to enable a truly immersive user experience.

[0005] In such AR/VR glasses, various types of refractive and diffractive lenses and beam-forming components are used to guide the light from a micro-display or a projector towards the human eye, allowing forming a virtual image that is superimposed with an image of the physical world seen with a naked eye (in case of AR glasses) or captured by a camera (in case of VR glasses).

[0006] Some of kinds of AR/VR glasses utilize optical waveguides wherein light propagates into the optical waveguide by TIR (for Total Internal Reflection) only over a limited range of internal angles. The

FoV (for Field of View) of the waveguide depends on the material of the waveguide. The FoV of a waveguide may be expressed as the maximum span of $\theta_1^+ - \theta_1^-$ which propagates into the waveguide by TIR. In some systems, the FoV is a function of the index of refraction of the material of the waveguide. For example, the FoV of a waveguide of refractive index n_2 may be given by: $\Delta\theta_1 = 2 \sin^{-1} \left(\frac{n_2-1}{2} \right)$. For $n_2 = 1.5$ the total field of view for a single mode system is rather limited to $\Delta\theta_1 = 28.96$ degrees. It can be seen that 60 degrees FoV is a practical limit for some types of waveguides because it is not generally feasible to use materials of refractive index above 2.0.

[0007] AR displays preferably fulfill certain criteria such as a high field of view, a large exit pupil and good uniformity along with light weight, and thin and compact size. Common NED technology solutions include freeform prisms, deformable mirrors, and holographic projection. For an eyeglass-like form factor that enables easy mobility and everyday use, an optical waveguide based design, such as those using diffractive waveguides with surface relief gratings as the diffractive elements, is one potential solution. Surface relief gratings are diffractive optical elements that serve to in-couple the incident light from the display source into the optical waveguide. Then, light is totally internally reflected inside the waveguide before being outcoupled towards the user's eyes with another grating.

[0008] Various designs have been proposed for use as in-coupler diffraction gratings in waveguide-based display systems. Some such structures use blazed surface relief structures to in-couple incident light energy into certain diffraction orders (usually $T_{\pm 1}$) that then propagate via Total Internal Reflection (TIR) inside the waveguide. Shi et al. propose a waveguide display design based on polarization dependent transmission metagratings (using T_{-1} diffraction order) that can achieve a horizontal FOV of 67° for $\lambda_{inc} = 460 \text{ nm}$ with a maximum efficiency of 60%. See Shi et al., "Wide field-of-view waveguide displays enabled by polarization dependent metagratings," Proc. SPIE 10676, Digital Optics for Immersive Displays, 1067615 (21 May 2018). Mattelin et al. report the design of blazed gratings on top of a waveguide material of index 1.49 that can achieve diffraction efficiencies for T_1 diffraction order as high as 48.4% for an incident wave illumination of wavelength $\lambda_{inc} = 543 \text{ nm}$. See Mattelin et al., "Design and fabrication of blazed gratings for a waveguide-type head mounted display," Optics Express, Vol. 28, No. 8 (2020). Xu et al. describes a system using a switchable phase grating using liquid crystals to direct incident energy into the second order. See Xu et al., "Large-angle and high-efficiency tunable phase grating using fringe field switching liquid crystal"; Optics Express 12274, Vol. 23, No. 9 (2015)

[0009] In some prior systems, reflective in-coupler gratings have non-symmetric designs making them efficient for only one half of the incident direction. Some systems use metallic components for reflection which would contribute to optical losses in a real system. Some systems use the first diffraction order to couple incident light into the waveguide.

SUMMARY

[0010] References in the specification to “one embodiment,” “an embodiment,” “an example embodiment,” and the like indicate that the embodiment described may include a particular feature, structure, or characteristic; but not every embodiment necessarily includes that particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, such feature, structure, or characteristic may be used in connection with other embodiments whether or not explicitly described.

[0011] A reflective diffraction grating according to some embodiments includes: a transparent medium having a first refractive index n_{WG} and an outer surface; and a periodic array of grating elements arranged in the transparent medium, the elements having a second refractive index $n_{element}$ greater than the first refractive index. The grating elements comprise: an outer region along the outer surface, the outer region being substantially rectangular in cross-section and having a first width d_{bottom} ; and an inner region extending inward from the outer region, the inner region being substantially rectangular in cross-section and having a second width d_{top} smaller than the first width. In some embodiments, the elements are symmetric in cross-section.

[0012] An apparatus according to some embodiments includes a plurality of diffractive elements, wherein each diffractive element comprises: a first region along an outer surface of a substrate, the first region being substantially rectangular in cross-section and having a first width d_{bottom} ; and a second region extending from the outer region, the second region being substantially rectangular in cross-section and having a second width d_{top} smaller than the first width, the second region being arranged substantially symmetrically on the outer region.

[0013] In some embodiments, the substrate is a transparent medium having a first refractive index n_{WG} and the diffractive elements have a second refractive index $n_{element}$ greater than the first refractive index.

[0014] In some embodiments, the first region is an outer region and the second region is an inner region extending inward from the outer region.

[0015] In some embodiments, the transparent medium is an optical waveguide.

[0016] In some embodiments, the diffraction grating is configured to diffract light with a selected free-space wavelength λ_0 , and the inner region has a height h_{top} substantially equal to λ_0 / n_{WG} .

[0017] In some embodiments, the diffraction grating is configured to diffract light with a selected free-space wavelength λ_0 , and the outer region has a height h_{bottom} substantially equal to $\lambda_0 / 2n_{WG}$.

[0018] In some embodiments, d_{bottom} is in the range of 720-830nm.

[0019] In some embodiments, d_{top} is in the range of 200-240nm.

[0020] In some embodiments, h_{top} is in the range of 390-480nm.

[0021] In some embodiments, h_{bottom} is in the range of 180-195nm.

[0022] A near-eye display according to some embodiments includes an image generator operative to generate an image; and a diffraction grating according to any of the embodiments described herein, wherein the transparent medium is a waveguide, and wherein the diffraction grating is operative to couple the image into the waveguide.

[0023] A method according to some embodiments includes: directing light on a plurality of diffractive elements, wherein each diffractive element comprises: a first region along an outer surface of a substrate, the first region being substantially rectangular in cross-section and having a first width d_{bottom} ; and a second region extending from the outer region, the second region being substantially rectangular in cross-section and having a second width d_{top} smaller than the first width, the second region being arranged substantially symmetrically on the outer region.

[0024] In some embodiments, the substrate is a transparent medium having a first refractive index n_{WG} , and the diffractive elements have a second refractive index $n_{element}$ greater than the first refractive index.

[0025] In some embodiments, the first region is an outer region and the second region is an inner region extending inward from the outer region.

[0026] In some embodiments, the diffractive elements are arranged periodically as a reflective diffraction grating.

[0027] In some embodiments, the transparent medium is part of an optical waveguide.

[0028] In some embodiments, the light is light representing an image.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIG. 1A is a cross-sectional schematic view of a waveguide display.

[0030] FIG. 1B is a schematic illustration of a binocular waveguide display with a first layout of diffractive optical components.

[0031] FIG. 1C is a schematic illustration of a binocular waveguide display with a second layout of diffractive optical components.

[0032] FIG. 1D is a schematic exploded view of a double-waveguide display.

[0033] FIG. 1E is a cross-sectional schematic view of a double-waveguide display.

[0034] FIG. 1F is a schematic perspective view of a waveguide-based optical image combiner used in some embodiments.

[0035] FIG. 2 is a schematic cross-sectional view of a field of view of a single-mode waveguide display.

- [0036]** FIG. 3 is a schematic cross-sectional view of a field of view of a dual-mode waveguide display.
- [0037]** FIG. 4 is a cross-sectional side view of a lens system that provides a real exit pupil.
- [0038]** FIG. 5 is a cross-sectional side view of a lens system suitable for use in some embodiments.
- [0039]** FIG. 6 is a cross-sectional view of a symmetric diffraction grating.
- [0040]** FIG. 7 is a cross-sectional view of another symmetric diffraction grating.
- [0041]** FIG. 8 is a cross-sectional view of a slanted diffraction grating.
- [0042]** FIG. 9 illustrates use of symmetric diffraction with non-symmetrical gratings that employs two different diffraction gratings.
- [0043]** FIG. 10 schematically illustrates typical diffraction efficiencies for the gratings of FIG. 9 as a function of the angle of incidence.
- [0044]** FIG. 11A is a cross-sectional view of a symmetric stepped diffraction grating profile.
- [0045]** FIG. 11B is a schematic illustration of coupling of light across different angles of incidence using a grating profile as in FIG. 11A.
- [0046]** FIG. 12A is a schematic cross-sectional view of an example diffraction grating unit cell, illustrating dimensions used in one embodiment.
- [0047]** FIG. 12B is a graph illustrating light intensity versus incident angle for second reflected diffraction orders of a grating using the unit cells of FIG. 12A.
- [0048]** FIG. 13 is a cross-sectional view of an example unit cell used in some embodiments.
- [0049]** FIGs. 14A-14B schematically illustrate an edge wave (HyD field component, Hy disturbance i.e. Hy with incident field propagation suppressed) pattern by an individual isolated inverse T-shaped element illuminated by a TE polarized EM wave for 0° (FIG. 14A) and 15° (FIG. 14B) incidence from inside the waveguide material.
- [0050]** FIGs. 15A-15B schematically illustrate edge wave (HyD field component) patterns by an individual isolated inverse T-shaped metallic element illuminated by a TE polarized EM wave for 0° (FIG. 15A) and 15° (FIG. 15B).
- [0051]** FIG. 16 is a schematic illustration indicating a direction of wave scattering.
- [0052]** FIG. 17 is a graph illustrating intensity variation of different reflection and transmission diffraction orders as a function of the incident EM wave angle inside the waveguide (θ_{inc}^{WG}).
- [0053]** FIG. 18 is a schematic cross-sectional view of a waveguide using a reflective diffraction grating according to an example embodiment.
- [0054]** FIG. 19 illustrates the intensity of the reflected second order (i.e. $R_{+2}+R_{-2}$) as a function of incident angles in air for a diffraction grating according to some embodiments.

[0055] FIG. 20A illustrates a diffraction grating unit cell with a perfect electric conductor (PEC) layer forming the surface relief features with the dimensions indicated in Table 1.

[0056] FIG. 20B illustrates intensities of different reflected orders for this grating as a function of incident angle inside the waveguide material.

[0057] FIG. 21A-21D schematically illustrates the simulated edge wave component HyD field component for a periodic arrangement of eleven unit cells. FIGs. 21A-21B illustrate results with $n_{\text{element}}=3.9$. In FIG. 21A, $\theta_{\text{inc}}^{\text{WG}} = 0^\circ$, and in FIG. 21B, $\theta_{\text{inc}}^{\text{WG}} = 15^\circ$. FIGs. 21C-21D illustrate results with metallized elements. In FIG. 21C, $\theta_{\text{inc}}^{\text{WG}} = 0^\circ$, and in FIG. 21D, $\theta_{\text{inc}}^{\text{WG}} = 15^\circ$.

[0058] FIG. 22 illustrates physical parameters of an example periodic unit cell structure.

DETAILED DESCRIPTION

[0059] Described herein are waveguide display systems and methods. An example waveguide display device is illustrated in FIG. 1A. FIG. 1A is a schematic cross-sectional side view of a waveguide display device in operation. An image is projected by an image generator 102. The image generator 102 may use one or more of various techniques for projecting an image. For example, the image generator 102 may be a laser beam scanning (LBS) projector, a liquid crystal display (LCD), a light-emitting diode (LED) display (including an organic LED (OLED) or micro LED (μ LED) display), a digital light processor (DLP), a liquid crystal on silicon (LCoS) display, or other type of image generator or light engine.

[0060] Light representing an image 112 generated by the image generator 102 is coupled into a waveguide 104 by a diffractive in-coupler 106. The in-coupler 106 diffracts the light representing the image 112 into one or more diffractive orders. For example, light ray 108, which is one of the light rays representing a portion of the bottom of the image, is diffracted by the in-coupler 106, and one of the diffracted orders 110 (e.g. the second order) is at an angle that is capable of being propagated through the waveguide 104 by total internal reflection.

[0061] At least a portion of the light 110 that has been coupled into the waveguide 104 by the diffractive in-coupler 106 is coupled out of the waveguide by a diffractive out-coupler 114. At least some of the light coupled out of the waveguide 104 replicates the incident angle of light coupled into the waveguide. For example, in the illustration, out-coupled light rays 116a, 116b, and 116c replicate the angle of the in-coupled light ray 108. Because light exiting the out-coupler replicates the directions of light that entered the in-coupler, the waveguide substantially replicates the original image 112. A user's eye 118 can focus on the replicated image.

[0062] In the example of FIG. 1A, the out-coupler 114 out-couples only a portion of the light with each reflection allowing a single input beam (such as beam 108) to generate multiple parallel output beams

(such as beams 116a, 116b, and 116c). In this way, at least some of the light originating from each portion of the image is likely to reach the user's eye even if the eye is not perfectly aligned with the center of the out-coupler. For example, if the eye 118 were to move downward, beam 116c may enter the eye even if beams 116a and 116b do not, so the user can still perceive the bottom of the image 112 despite the shift in position. The out-coupler 114 thus operates in part as an exit pupil expander in the vertical direction. The waveguide may also include one or more additional exit pupil expanders (not shown in FIG. 1A) to expand the exit pupil in the horizontal direction.

[0063] In some embodiments, the waveguide 104 is at least partly transparent with respect to light originating outside the waveguide display. For example, at least some of the light 120 from real-world objects (such as object 122) traverses the waveguide 104, allowing the user to see the real-world objects while using the waveguide display. As light 120 from real-world objects also goes through the diffraction grating 114, there will be multiple diffraction orders and hence multiple images. To minimize the visibility of multiple images, it is desirable for the diffraction order zero (no deviation by 114) to have a great diffraction efficiency for light 120 and order zero, while higher diffraction orders are lower in energy. Thus, in addition to expanding and out-coupling the virtual image, the out-coupler 114 is preferably configured to let through the zero order of the real image. In such embodiments, images displayed by the waveguide display may appear to be superimposed on the real world.

[0064] Some waveguide displays includes more than one waveguide layer. Each waveguide layer may be configured to preferentially convey light with a particular range of wavelengths and/or incident angles from the image generator to the viewer.

[0065] As illustrated in FIGs. 1B and 1C, waveguide displays having in-couplers, out-couplers, and pupil expanders may have various different configurations. An example layout of one binocular waveguide display is illustrated in FIG. 1B. In the example of FIG. 1B, the display includes waveguides 152a, 152b for the left and right eyes, respectively. The waveguides include in-couplers 154a,b, pupil expanders 156a,b, and components 158a,b, which operate as both out-couplers and horizontal pupil expanders. The pupil expanders 156a,b are arranged along an optical path between the in-coupler and the out-coupler. An image generator (not shown) may be provided for each eye and arranged to project light representing an image on the respective in-coupler.

[0066] An layout of another binocular waveguide display is illustrated in FIG. 1C. In the display of FIG. 1C, the display includes waveguides 160a, 160b for the left and right eyes, respectively. The waveguides include in-couplers 162a,b. Light from different portions of an image may be coupled by the in-couplers 162a,b to different directions within the waveguides. In-coupled light traveling toward the left passes through pupil expanders 164a,b and 165a,b, while in-coupled light traveling toward the right passes through pupil expanders 166a,b and 167a,b. Having passed through the pupil expanders, light is coupled

out of the waveguides using out-couplers 168a,b to substantially replicate an image provided at the in-couplers 162a,b.

[0067] In different embodiments, different features of the waveguide displays may be provided on different surfaces of the waveguides. For example (as in the configuration of FIG. 1A), the in-coupler and the out-coupler may both be arranged on the anterior surface of the waveguide (away from the user's eye). In other embodiments, the in-coupler and/or the out-coupler may be on a posterior surface of the waveguide (toward the user's eye). The in-coupler and out-coupler may be on opposite surfaces of the waveguide. In some embodiments, one or more of an in-coupler, an out-coupler, and a pupil expander, may be present on both surfaces of the waveguide. The image generator may be arranged toward the anterior surface or toward the posterior surface of the waveguide. The in-coupler is not necessarily on the same side of the waveguide as the image generator. Any pupil expanders in a waveguide may be arranged on the anterior surface, on the posterior surface, or on both surfaces of the waveguide. In displays with more than one waveguide layer, different layers may have different configurations of in-coupler, out-coupler, and pupil expander.

[0068] FIG. 1D is a schematic exploded view of a double waveguide display, including an image generator 170, a first waveguide (WG₁) 172, and a second waveguide (WG₂) 174. FIG. 1E is a schematic side-view of a double waveguide display, including an image generator 176, a first waveguide (WG₁) 178, and a second waveguide (WG₂) 180. The first waveguide includes a first transmissive diffractive in-coupler (DG1) 180 and a first diffractive out-coupler (DG6) 182. The second waveguide has a second transmissive diffractive in-coupler (DG2) 184, a reflective diffractive in-coupler (DG3) 186, a second diffractive out-coupler (DG4) 188, and a third diffractive out-coupler (DG5) 190. Different displays may use different arrangements of optical components (such as different arrangements of pupil expanders) on the first and second waveguides.

[0069] FIG. 1F is a schematic perspective view of a waveguide-based optical image combiner used in some embodiments. In the configuration of FIG. 1F, a light engine 192 includes an image display 193 and lens or lenses 194 that direct the image onto in-coupler grating 195, which couples the image into the waveguide 196 toward eye pupil expander 197, which in turn directs the image to out-coupler grating 198.

[0070] While FIGs. 1A-1F illustrate the use of waveguides in a near-eye display, the same principles may be used in other display technologies, such as head up displays for automotive or other uses.

[0071] Example embodiments describe herein provide a symmetric design of a reflection-type grating for the second diffraction order. Some such embodiments are configured to operate without any metallized surfaces. In some embodiments the grating is configured for an incident wavelength of 625 nm. It should be understood that other embodiments may be configured for other wavelengths, e.g. by scaling the physical dimensions of the grating components in proportion to changes in the incident wavelength.

[0072] The use of the second diffraction order facilitates the use of relatively bigger grating period (compared to that obtained by the use of the first diffraction order) and grating element dimensions which are favorable from a fabrication point of view. Moreover, example embodiments use a symmetric diffraction grating element that splits the pupil in angular space, allowing a higher field of view and relatively low light losses due to symmetric angles of the light engine. Example embodiments can be scaled and adapted for other wavelengths of the EM spectrum.

[0073] For waveguides based on diffraction gratings with an optical system generating a synthetic image to be superimposed in the field of view, it is desirable for lens systems to have real and not virtual exit pupils. In other words, its exit pupil location is external to the lens, and it is also at the same time the aperture stop of the lens.

[0074] The lens system of FIG. 4 provides an appropriate exit pupil. The system has a disk-shaped aperture stop whose diameter is dependent on the diameter of the lens that limits the most its size. As there are no lenses after that aperture stop, it is the image of itself and hence the exit pupil. It is at this place or at the vicinity thereof that the in-coupler may be set.

[0075] A lens system may be referred to as afocal if either one of the object or the image is at infinity. The lens system of FIG. 4 is afocal on the image side as the rays leaving the lens are parallel for each field and there is an image at infinity.

[0076] A point position on an object may be referred to as a field. FIG. 4 illustrates rays leaving five different fields. In some cases, a pixel may be considered to be field. The size of a pixel may be assumed to be negligible as compared to other quantities in the system.

[0077] As seen in FIG. 4, each field's rays are spilled over the whole exit pupil. Hence, if we aperture down the exit pupil, we will homogeneously also cut-off on pixel's number of rays, for all fields at the same time, which means the light intensity will go down. This is the functionality of the aperture stop and this demonstrates that the exit pupil and the aperture stop are the same in that lens and that the exit pupil is real and not virtual.

[0078] The pupil can be tiled spatially. This means that the positive side of the pupil (rays hitting the pupil at $y > 0$) will undergo one diffraction process, while rays hitting the pupil at the negative side ($y < 0$), will undergo another diffraction process. The origin of the y axis is the optical axis. The rays hitting the pupil with some angular sign will undergo a particular process, while those hitting with the opposite sign will undergo another diffraction process. Alternatively, pupil angular tiling may lead to rays with a range $[\theta_1, \theta_2]$ being diffracted into one direction in the waveguide while rays with $[-\theta_1, -\theta_2]$ are diffracted into the opposite direction.

[0079] Another property of an afocal lens is to map all pixels from the display, which are referenced by their respective position in a cartesian coordinates by their (x,y) coordinates on the display, into a spherical coordinate system. With respect to FIG. 4, consider the image plane to be in the x-y plane, with the y-axis extending up and down on the page and the x-axis being perpendicular to the page. After the afocal lens system, the rays issued from one single field cannot be referenced by x or y since they spread, but they all have a unique direction which is different from one pixel to another. The lens converts pixel (x,y) coordinates to a spherical (θ, Φ) pair. This means that for each ray's direction in the exit pupil (or in-coupler) we deal with another pixel.

[0080] In the example of FIG. 5, the rays from fields with $y > 0$ and the rays from fields with $y < 0$ have angles with opposite sign at the exit pupil in a polar coordinate system. If we use a spherical coordinate system with the z-axis pointing along the optical axis, then the polar angles are always between 0 and π (positive) and only the azimuthal direction sign will distinguish the rays hitting the exit pupil 'from above' or 'from below'. At each position along the exit pupil, we have positive as well as negative ray directions in a polar coordinate system.

[0081] When symmetric diffraction modes are used, the diffraction grating will diffract an incoming ray in the plus or minus order. In some cases, if the ray has one particular sign orientation, it will diffract in one mode, and if the sign changes, it will diffract into the opposite mode. In fact, mathematically, the diffraction occurs always in all modes. Hence what we mean here is that if for a particular direction of incoming ray we diffract into a particular mode, the energy in that mode is stronger than in the mode of opposite sign. Symmetric here means that if a plus direction diffracts efficiently into the mode M, the minus direction will diffract efficiently into the -M direction. (M is a relative natural number.)

[0082] A symmetric diffraction grating generally permits the previous property of symmetric diffraction modes. This property may be effected with the use of a basic structure (elementary pitch) that has a left-right geometrical symmetry. Blazed and slanted grating are not symmetric diffraction gratings. Grating based on square shape steps (door shape) can be symmetric diffraction gratings. FIGs. 6 and 7 offer examples of symmetric diffraction gratings.

[0083] Example embodiments use symmetric diffraction gratings that can achieve symmetric diffraction modes of very high efficiency. For opposite signed angle of incidence, some embodiments provide +M or -M diffraction modes of high efficiency.

[0084] FIG. 8 illustrates a slanted grating which, when illuminated from above, will be efficient for rays tilted toward the left (negative angles in our case) and will have the best diffraction mode towards the right hand side. When illuminated from the right hand side (positive angle), the diffraction mode toward the left will be very weak.

[0085] FIG. 9 illustrates use of symmetric diffraction with non-symmetrical gratings that employs two different diffraction gratings. The in-coupling grating in FIG. 9 has asymmetric groove profiles. The grating is split in two parts, each coupling mainly to one direction. In the system of FIG. 9, rays on the left-hand side will diffract with high efficiency toward the left, those on the right-hand side will diffract to the right, with high efficiency for a limited angular range. In addition to that process, a small part of the energy will also diffract into the opposite direction for the opposite diffraction mode.

[0086] In a grating as in FIG. 9, only rays hitting the right hand side grating with negative direction of propagation will efficiently diffract into the right hand side diffraction mode. Rays hitting the right hand side diffraction grating with positive angles of incidence will not diffract into the right hand side diffraction mode. (They will in fact but with a low intensity.) Only rays hitting the left hand side grating with positive direction of propagation will efficiently diffract into the left hand side diffraction mode. Rays hitting the left hand side diffraction grating with negative angles of incidence will diffract into the left hand side diffraction mode only with a low intensity. As, at each position of the exit pupil, there is an equal distribution of positive and negative angles of propagation approximately half of the light will be lost. FIG. 10 illustrates typical diffraction efficiencies for both gratings as a function of the angle of incidence.

[0087] In contrast, a diffraction grating with a profile as illustrated in FIG. 11A, which is used in some embodiments, provides for more even coupling of light across different angles of incidence, as is illustrated schematically in FIG. 11B.

[0088] FIGs. 2 and 3 illustrate differences between a single-mode solution (FIG. 2) and a dual-mode system (FIG. 3). In a single mode system, one single diffraction mode is used to carry the image: either +1 or -1 diffraction mode. In a dual-mode system, a grating (which may be symmetric) diffracts one half of the field of view into one direction using a positive diffraction order and the other half into the opposite direction using the negative diffraction order. Some example embodiments described herein use diffraction orders of ± 2 .

[0089] In some embodiments of this disclosure, edge wave phenomena are used in selecting the parameters of the in-coupling diffraction grating, which serves to diffract the incident EM energy into the 2nd reflection order while maintaining a large angular tolerance.

[0090] The present disclosure provides diffraction grating elements that may be used as a reflective in-coupler grating that uses the second diffractive order. Reflective characteristics of grating elements in some embodiments may be of use in specific optical designs involving beam folding. Example embodiments of a grating show good diffraction efficiency along with high uniformity which may enhance an immersive viewing experience. Furthermore, use of the second order may ease the fabrication constraints relating to the grating period and grating element dimensions compared to use of the first order. Example symmetric diffraction grating elements may be understood as splitting the pupil in angular space, allowing higher field

of view and low light losses due to symmetric angles of the light engine. Example embodiments further allow the grating elements to be inside the guiding material, which may be advantageous from a practical standpoint as they are protected e.g. from dust particles or mechanical impacts.

[0091] Described herein are diffraction gratings using unit cell elements with dimensions that, when placed periodically in a 1D array, diffract the incident EM radiation with high efficiency and uniformity into the $\pm 2^{\text{nd}}$ reflection order. FIG. 12A is a schematic cross-sectional view of the an example unit cell along with physical dimensions used in one embodiment. The system includes of a waveguide material of refractive index n_{WG} , surrounded by air, hosting the unit cell element of a material with an index of n_{element} . Using COMSOL Multiphysics software that numerically solves Maxwell's equations using finite-element-method, FIG. 12B shows the diffraction efficiency curve for the $\pm 2^{\text{nd}}$ reflection order as a function of the incident angle in air. The incident wavelength is denoted by $\lambda_0 = 625\text{nm}$ corresponding to red color of the visible spectrum and is TE polarized.

[0092] FIG. 12A is a schematic cross-sectional view of an example diffraction grating unit cell, illustrating dimensions used in one embodiment. FIG. 12B is a graph illustrating light intensity versus incident angle for second reflected diffraction orders of a grating using the unit cells of FIG. 12A.

[0093] As seen in FIG. 12B, the second order diffraction efficiency is at least 50% for a range of incidence angles from -25.7° to $+25.7^\circ$ (this is the range of incident angles in air that can be coupled inside the waveguide) resulting in a field of view (FoV) of 51.4° for the waveguide with a diffraction uniformity of 83.3% in this range. This optical response in the far-field is attributed to a constructive interference of EM waves scattered by the edges of the proposed inverse T-shaped periodic grating element. The near-field EM wave pattern of an individual isolated grating element is analyzed below to provide geometrical relations associated with the physical dimensions of the grating element. Following that, a link is shown between the near-field EM wave pattern of a periodic arrangement of 11 unit cells and its relation to the observed far-field response. These results are then compared to use of a Perfect Electric Conductor (PEC) surface relief structure having the same physical dimensions to demonstrate the effect of the choice of the grating element material, n_{element} . The tolerances of example physical dimensions are also discussed.

Inverse T-shaped unit cell optical characteristics

[0094] A cross-sectional view of an example unit cell used in some embodiments is presented in FIG. 13. The element has a refractive index denoted by n_{element} and is embedded inside the guiding material of refractive index n_{WG} with air (index n_{air}) as the surrounding host medium around the waveguide. For descriptive purposes, the example embodiments are described here with reference to the use of TE polarized light ($\vec{E} = \{0,0,1\}$) for which the edge waves manifest themselves in the magnetic field

component H_y , although other embodiments may use light with other polarizations. Numerical calculations described herein were carried out using *COMSOL Multiphysics*.

[0095] FIG. 13 illustrates that, upon illumination by a linearly polarized EM wave, it is possible to observe an intensive field scattered in the inner region of the element with refractive index $n_{element}$. Four edge waves (illustrated as dashed arrows) generated by the vertical edges after multiple reflection by the walls of this element and interference will provide very intensive field distribution inside the element. Taking into account the formula for angle of edge wave deviation (θ_{edge}), it is possible to conclude that the main part of an edge wave field will stay inside the element due to the total internal reflection (TIR) phenomenon.

[0096] The angle of the generated edge wave for normal incidence with respect to the vertical is approximately given by the following relation:

$$\theta_{edge} \cong 90^\circ - \sin^{-1} \left(\frac{n_{WG}}{n_{element}} \right) \quad (1)$$

[0097] For the chosen combination of materials, this angle being greater than the critical angle for total internal reflection causes the edge waves to get reflected by the opposite walls of the material and cause most of the energy to be concentrated inside the high refractive index material element. For example, for the normal incidence at the system with $n_{element} = 3.9 + i0$ (the material losses are not considered here) and $n_{WG} = 1.52$, angle of edge wave propagation is equal to $\theta_{edge} \cong 67^\circ$ and critical angle θ_c for boundaries between material of a waveguide and material of an element is equal to $\theta_c = \sin^{-1} \left(\frac{n_{WG}}{n_{element}} \right) = 23^\circ$, θ_c for boundaries between material of an element and host medium is equal to $\theta_c = \sin^{-1} \left(\frac{n_{air}}{n_{element}} \right) = 15^\circ$. Due to the specific propagation of the edge wave inside the element (including forward and backward EM fluxes) and boundary conditions at the edges, a small portion of edge wave field will escape the element. Some energy leaks out in the form of evanescent waves and recombines with the backward flux transmitted up to form the reflected lobe of interest.

[0098] FIGs. 14A-14B show the edge wave pattern (excluding the incident wave contributions) for an individual isolated inverse T-shaped element illuminated by a TE polarized incident wave with $\theta_{inc} = 0^\circ$ and 15° where it is possible to observe that a good portion of the energy of the generated edge waves is reflected into the incident medium. FIGs. 15A-15B illustrate the field distribution inside the waveguide material for a case of a metallic inverse T-shaped element for the same angles of electromagnetic wave incidence and having the same physical dimensions. The comparison of corresponding figures of FIGs. 14A-14B with those of FIGs. 15A-15B (for an isolated grating element case) and also of FIGs. 21A-21D (for a periodic array of 11 unit cells) illustrates that the position and angle of deviation for the lobes observed in the waveguide outside the element is the result of constructive interference between the waves scattered outside the high refractive index inverse T-shaped element. For high refractive index $n_{element}$ these

angles will be almost independent on the material of element. Combination of the materials will primarily affect the intensity of scattered waves.

[0099] By using the characteristics of the unit cell element, it is possible to place similar structures next to one another to reinforce the scattered field energy into a direction that corresponds to an order, which will be in-coupled into the waveguide, to increase its diffraction efficiency. Other directional waves as seen in FIGs. 14A-14B will not be reinforced when they do not correspond to proper order of a diffraction grating. In addition to the refractive index-ratio between the guiding medium material and the unit cell element material, there are other physical dimensions such as the width and height of individual edges that allow for manipulation of the reflected scattered field in the system.

[0100] FIGs. 14A-14B schematically illustrate an edge wave (HyD field component) pattern by an individual isolated inverse T-shaped element illuminated by a TE polarized EM wave for 0° (FIG. 14A) and 15° (FIG. 14B) incidence from inside the waveguide material.

[0101] FIGs. 15A-15B schematically illustrate an edge wave (HyD field component) pattern by an individual isolated inverse T-shaped metallic element illuminated by a TE polarized EM wave for 0° (FIG. 15A) and 15° (FIG. 15B).

[0102] In selecting parameters of the inverse T-shaped element, it is desirable to take into account constructive interference phenomenon for the cylindrical waves scattered by the tips/edges of the element inside the material of a waveguide. For the H_y field component in TE mode, the phases of cylindrical waves generated by the opposite edges will be opposite. So, to observe a constructive interference between the scattered waves in the desirable direction for proposed n_{WG} , the width of the top part of inverse T-shaped element may be selected to satisfy the following condition:

$$d_{top} = \frac{1}{2} \frac{p\lambda_0}{n_{WG}(\sin \beta_p + \sin \theta_{inc}^{WG})}, \quad (2)$$

where p is the number of half waves which interfere constructively (for the proposed parameters $p=1$), β_p is the angle between the diffracted ray and the normal to the surface of the top part. (The top part of the element connects tips A and B of the elements as seen in FIG. 13.) To provide the maximal input of the scattered field into the far-field response of the system, β_p may be selected to be close to the angle of diffracted rays which will be in-coupled by the waveguide. For an example dual-mode solution for the low angles of incidence (close to the normal incidence) $\beta_p \cong 75^\circ$, and for maximal angles of incidence limited by TIR phenomenon inside the waveguide, $\beta_p \cong \theta_{TIR}$, where θ_{TIR} is a critical angle for the boundary between material of the waveguide and host medium. In some embodiments, parameters are selected to provide better uniformity.

[0103] For a case of normal incidence, simulations do not reflect an impact of the additional block with the tips C and D. It becomes significant for an inclined incidence when the reflectivity of corresponding

order will be increased due to the input of the rays that arise from the constructive interference between the cylindrical waves scattered by the tips/edges of the top part of an element and the cylindrical waves scattered by the tips/edges of the bottom part of an element inside the material of a waveguide.

[0104] FIG. 16 is a schematic illustration indicating a direction of wave scattering. FIG. 16 illustrates a direction 2002 of incident light and a direction 2004 of light that experiences constructive interference.

[0105] As the result of constructive interference for the tips A and C (or tips B and D), as shown in FIG. 16, the angle between the diffracted ray and the normal to the top part of an element will be equal to:

$$\sin(\gamma_q) - \sin\{(\theta' - \theta_{\text{inc}}^{\text{WG}})\} = q \frac{\lambda_{\text{WG}}}{d'} \quad (3)$$

where $d' = \left(\left(\frac{d_{\text{bottom}} - d_{\text{top}}}{2} \right)^2 + h_{\text{top}}^2 \right)^{\frac{1}{2}}$ is the distance between the tips A and C, q is the number of the wavelengths which interfere constructively, $\tan \theta' = 2 \left(\frac{h_{\text{top}}}{d_{\text{bottom}} - d_{\text{top}}} \right)$. For this example, $q=-1$. To enhance the input of these rays into the far field response (characterized by angle β with respect to the vertical), the parameters of the element may be selected to satisfy the following condition: $(\gamma_q + \theta') \cong \beta_{p=1}$. For example, the parameters may be chosen such that for $\theta_{\text{inc}}^{\text{WG}} = 15^\circ$, $\gamma_{-1} = -8.6^\circ$ and so, $(\gamma_{-1} + \theta') = -8.6 + 54.96^\circ = 46^\circ$ which is very close to the value $\beta_{p=1}=43.17^\circ$, the angle of the second reflection order for an example unit cell grating as predicted by the grating equation.

[0106] To increase the intensity of scattered waves inside the waveguide, example embodiments use

$$h_{\text{top}} = \frac{\lambda_0}{n_{\text{WG}}}, h_{\text{bottom}} = \frac{1}{2} \frac{\lambda_0}{n_{\text{WG}}}. \text{ In this case, } d_{\text{bottom}} \text{ can be determined using Equation 3.}$$

To provide the better diffraction uniformity, the parameters of the system may be selected taking into account a field of view of a system in which the grating is to be used. The effect of the material of diffraction grating elements on the far field distribution may be observed by comparing the reflectivity for an example system with the reflectivity of a system using metallic elements.

Far-field response of periodically arranged unit cells

[0107] The period for a symmetric diffraction grating to couple the m^{th} diffraction order into the waveguide may be expressed as:

$$d = m \frac{\lambda_0}{n_{\text{WG}} * \sin \theta_{\text{max}} - \sin \theta_{\text{min}}} \quad (4)$$

where m is the diffraction order, n_{WG} is the Refractive Index (RI) of the optical waveguide, and $\theta_{\text{max,min}}$ are the maximum and minimum angles that can be coupled inside the waveguide. Substituting values of $m = 2$, $\lambda_0 = 625 \text{ nm}$, $n_{\text{WG}} = 1.52$, $\theta_{\text{max}} = 75^\circ$ and $\theta_{\text{min}} = 2^\circ$ results in $d = 872.1 \text{ nm}$. FIG. 17 shows the numerically calculated angle dependence of the various diffraction orders generated for a grating with the above-calculated period with the proposed unit cell as the grating element. As mentioned in

the previous section, there are various physical parameters that play a role in the manipulation of the generated edge waves and these parameters may be selected to generate desired diffraction curves are produced. Table 1 tabulates the various parameters of the diffraction grating.

Period, d (nm)	RI of waveguide, n_{WG}	RI of element, $n_{element}$	$d_{bottom}(nm)$	$h_{bottom}(nm)$	$d_{top}(nm)$	$h_{top}(nm)$
872.1	1.52	3.9	822	191	226	425

Table 1: parameters of an example inverse T-shaped unit cell

[0108] In some embodiments, the waveguide is glass and the grating elements are silicon. In some embodiments, the ratio between the element material refractive index and the waveguide material refractive index is high (e.g. above 2). Different materials may be used in other embodiments.

[0109] The unit cell grating, being symmetric in design, diffracts the $\pm m^{th}$ diffraction orders symmetrically with respect to normal incidence of light. Two parameters that characterize the optical performance of such a grating are its diffraction efficiency (DE) and diffraction uniformity (DU). Diffraction efficiency may be expressed as the ratio of the intensities of the m^{th} diffraction order to the incident light, $DE_m = \frac{I_m}{I_{inc}}$. Diffraction uniformity is a measure of the homogeneity of the diffraction efficiency for all angles that are in-coupled into the waveguide. It may be expressed as follows.

$$DU = 1 - \left(\frac{\eta_{max} - \eta_{min}}{\eta_{max} + \eta_{min}} \right) \quad (5)$$

[0110] From FIG. 17 it may be observed that the grating can diffract the incident energy into the $\pm 2^{nd}$ orders with a good uniformity. The remainder of the incident energy is mainly being transferred to the transmission and other reflected orders.

[0111] FIG. 17 is a graph illustrating intensity variation of different reflection and transmission diffraction orders as a function of the incident EM wave angle inside the waveguide (θ_{inc}^{WG}). The range of θ_{inc}^{WG} is restricted to the angles that can be coupled inside the waveguide (e.g. $\pm 16.58^\circ$). The unit cell parameters of the diffraction grating are those listed in Table 1.

[0112] In FIG. 17, θ_{inc}^{WG} corresponds to the angles of incidence (in degrees) within the guiding medium. The actual incident angles coming from the light engine are from the surrounding air medium, denoted by θ_{inc}^{air} (see FIG. 18).

[0113] FIG. 18 is a schematic cross-sectional view of a waveguide using a reflective diffraction grating according to an example embodiment. FIG. 18 illustrates the different angles of incidence in air (θ_{inc}^{air}) and in the waveguide (θ_{inc}^{WG}) of light from a light engine.

[0114] To determine the corresponding incident angles in air, the Snell-Descartes relation may be used:

$$n_{air} \sin \theta_{inc}^{air} = n_{WG} \sin \theta_{inc}^{WG}$$

where the subscripts *air* and *WG* correspond to the surrounding air and the guiding mediums, respectively. Using this relation FIG. 19 shows the diffraction efficiency (DE) for the sum of $\pm 2^{nd}$ orders for the corresponding incident angles in air θ_{inc}^{air} that can be coupled into the waveguide by total internal reflection. For the range of incident angles in air that can be coupled inside the waveguide ($\pm 25.7^\circ$), at least 50% of the incident energy is being reflected into the second diffraction order with a DU of 83.3%. The edge waves produced by different edges of the periodic structure may contribute to this far-field response.

[0115] FIG. 19 illustrates the intensity of the reflected second order (i.e. $R_{+2}+R_{-2}$) as a function of incident angles in air for a diffraction grating according to some embodiments.

[0116] For a comparison, FIG. 20B shows the simulated far-field response of a diffraction grating with a perfect electric conductor (PEC) layer forming the surface relief features in the guiding material with the same physical dimensions as indicated in Table 1. FIG. 20A is a schematic cross-sectional view of a grating element as used in generating the results of FIG. 20B. As seen in FIG. 20B, the incident energy is primarily distributed between the specular reflection order, R_0 and the $\pm 2^{nd}$ orders. The diffraction efficiency of either of these orders is less than 50% (within the FoV angles) which is not favorable for practical applications. This illustrates the effects of selecting the refractive index of the grating element ($n_{element}$) as it aids in suppressing the energy going into the specular order, R_0 and redirects it into the $\pm 2^{nd}$ orders (as shown in FIG. 17). Below, a range of $n_{element}$ values is described for use in example embodiments with the parameters mentioned in Table 1 that will give a high diffraction efficiency ($\cong 50\%$) for the $\pm 2^{nd}$ orders.

[0117] FIG. 20A illustrates a diffraction grating unit cell with a perfect electric conductor (PEC) layer forming the surface relief features with the same dimensions indicated in Table 1. FIG. 20B illustrates intensities of different reflected orders for this grating as a function of incident angle inside the waveguide material.

Near-field to far-field relation

[0118] To describe the far-field response in terms of the near field edge wave pattern, is it possible to use of the grating equation in reflection mode:

$$n_{WG}(\sin \theta_m + \sin \theta_{inc}^{WG}) = m \left(\frac{\lambda_0}{d} \right) \quad (6)$$

where, n_{WG} is the refractive index of the incident medium, θ_m is the angle of the m^{th} diffraction order from the vertical, and θ_{inc}^{WG} is the incident angle from the vertical inside the waveguide. Using this equation, one can determine the angle of the second diffraction order as a function of the incident angle. FIG. 21A-21D schematically shows the near-field pattern of the edge waves for a periodic array of an example proposed unit cell for $\theta_{inc}^{WG} = 0^\circ$ and 15° . In an example embodiments, the allowed range of θ_{inc}^{WG} is $\pm 16.58^\circ$. Outside this range, the light will not get coupled inside the waveguide.

[0119] FIG. 21A-21D schematically illustrates the simulated edge wave component HyD field component for a periodic arrangement of eleven unit cells. FIGs. 21A-21B illustrate results with $n_{\text{element}}=3.9$. In FIG. 21A, $\theta_{\text{inc}}^{\text{WG}} = 0^\circ$, and in FIG. 21B, $\theta_{\text{inc}}^{\text{WG}} = 15^\circ$. FIGs. 21C-21D illustrate results with metallized elements. In FIG. 21C, $\theta_{\text{inc}}^{\text{WG}} = 0^\circ$, and in FIG. 21D, $\theta_{\text{inc}}^{\text{WG}} = 15^\circ$.

[0120] Table 2 shows a comparison between the angle of the second reflection order predicted by the grating equation and the angle that the edge waves make for a periodic array of the proposed unit cell for two values of θ_{inc} . The angles are measured with respect to the vertical.

<i>Incident angle inside waveguide, $\theta_{\text{inc}}^{\text{WG}} (^\circ)$</i>	<i>Angle of 2nd reflected order, θ_2 predicted by grating equation ($^\circ$)</i>	<i>Angle (approx.) made by edge waves for a periodic array ($^\circ$)</i>
0	70.6	69.8
15	43.17	43.4

Table 2: Comparison of the angles predicted by the grating equation and the edge waves simulated.

[0121] It can be seen that there is a good coherence between the angles of the second reflected order predicted by the grating equation (Equation 6) and the angles of the edge wave component HyD field component getting scattered by the inverse T-shaped grating element. In spite of this good coherence, the intensity of the $\pm 2^{\text{nd}}$ orders for $\theta_{\text{inc}}^{\text{WG}} = 0^\circ$ is only 27% each (FIG. 17), which may be explained by the fact that the resultant edge waves of one unit cell are not in-phase with those of its neighboring unit cell for the calculated grating period of 872.1 nm (refer to Equation 4).

Parametric variations of unit cell dimensions

[0122] Different parameters of a unit cell may be selected to provide a desired far-field optical response. Parameters such as n_{element} and other physical dimensions affect the response of the reflected second diffraction order as a function of the incident angle inside the waveguide, $\theta_{\text{inc}}^{\text{WG}}$. For embodiments that use a symmetrical diffraction grating element, it is sufficient to analyze only one-half of the incident angle range (here, $+\theta_{\text{inc}}^{\text{WG}}$) and in that case, the reflected diffraction order of interest is R-2. For the case of $-\theta_{\text{inc}}^{\text{WG}}$ angles, it would be the R+2 order that would be of interest.

[0123] The optical response of the inverse T-shaped element may be understood based on the constructive interference of the the optically scattered EM waves by the tips of the element. For a given value of n_{WG} and set of physical parameters (which may be calculated using the relations describe herein), this far-field response is valid only for a range of materials of the grating element. The effect of n_{element} variation on the reflected second order as a function of the incidence angle has been investigated. It has been observed that there is a range of n_{element} values (i.e. $\Delta n_{\text{element}} = 3.7 - 4$) for which the R-2 Diffraction

Efficiency (DE) is approximately 50% or higher. Outside this range, the DE is lower, and although inside the range it is high, its uniformity is best close to $n_{\text{element}}=3.9$.

[0124] FIG. 22 illustrates physical parameters of an example periodic unit cell structure.

[0125] An investigation has been conducted of the effect of variations in the physical dimensions (e.g. d_{bottom} , d_{top} , h_{top} , h_{bottom}) of the inverse T-shaped grating element on the reflected second order as a function of the incident angle inside the waveguide ($\theta_{\text{inc}}^{\text{WG}}$), respectively, for an incident wavelength of 625 nm. Based on this investigation, example ranges of physical parameters that may advantageously be used in some embodiments are indicated in Table 3:

<i>Physical parameter</i>	<i>Approx. range (nm) for which diffraction efficiency of $R_{\pm 2}$ order is $\approx 50\%$</i>	<i>Value (nm) for which diffraction efficiency of $R_{\pm 2}$ order is $\approx 50\%$ and uniform within the field of view</i>
d_{bottom}	720-830	822
d_{top}	200-240	226
h_{top}	390-480	425
h_{bottom}	180-195	191

Table 3: Range of values along with an example selected value for different physical parameters of the inverse T-shaped element.

[0126] These example ranges were selected to achieve high diffraction efficiency for the second reflection order. Once the range is determined, a final value for each physical parameter may be selected to achieve high diffraction uniformity.

[0127] Example embodiments provide a reflective diffractive grating which incouples light with a wide field of view inside a waveguide. For instance, with a waveguide index 1.52, a field of view upto 50° can be reached.

[0128] Example parameter ranges have been described for parameters such as n_{element} , d_{bottom} , d_{top} , h_{top} and h_{bottom} for which the grating reflects atleast 50% of the incident energy into the second diffraction order. Embodiments that use other parameter ranges may be generated by scaling the selected parameters to accommodate different wavelengths or by other techniques.

[0129] Various different embodiments may use different refractive indices of the waveguide and of the grating elements.

[0130] In some embodiments, no metallization is used on the grating elements.

[0131] Some embodiments use a symmetric diffraction grating element that splits the pupil in angular space, allowing higher field of view and no light losses due to symmetric angles of the light engine.

[0132] In some embodiments, use of the second diffraction order permits the use of a relatively bigger grating period and a bigger grating element size (compared to those associated with first order diffraction gratings) which is desirable from a fabrication view point.

[0133] In some embodiments, the diffractive structure lies inside the light-guiding material, hence can be relatively more protected than if it were protruding above it.

[0134] Example embodiments may be fabricated using standard microfabrication facilities.

[0135] While the grating structures are primarily described herein for use as diffractive in-couplers for waveguide displays, such structures may also be used as diffractive out-couplers or in other diffraction grating applications, or in applications combining diffractive elements. Applications of the grating structures described herein are not limited to visible light applications. With appropriate changes to the dimensions of grating elements and their spacing, embodiments may be used for electromagnetic wavelengths longer or shorter than those of visible light. In those cases, descriptions that refer to transparency, opacity, reflectivity, refractive indices, and the like should be understood with respect to the relevant wavelengths.

[0136] In the present disclosure, modifiers such as “first,” “second,” “third,” and the like are sometimes used to distinguish different features. These modifiers are not meant to imply any particular order of operation or arrangement of components. Moreover, the terms “first,” “second,” “third,” and the like may have different meanings in different embodiments. For example, a component that is the “first” component in one embodiment may be the “second” component in a different embodiment. Similarly, modifiers such as “top” and “bottom” or “upper” and “lower” are used only to distinguish relative positions of different features; it should be understood that, depending on how an apparatus is oriented, a portion described as the “top” or “upper” portion may temporarily or permanently be in a lower position, a leftward position, a rightward position, and so on, without departing from the principles described herein.

[0137] Although features and elements are described above in particular combinations, one of ordinary skill in the art will appreciate that each feature or element can be used alone or in any combination with the other features and elements.

CLAIMS

What is Claimed:

1. An apparatus comprising:
 - a plurality of diffractive elements, wherein each diffractive element comprises:
 - a first region along an outer surface of a substrate, the first region being substantially rectangular in cross-section and having a first width d_{bottom} ; and
 - a second region extending from the outer region, the second region being substantially rectangular in cross-section and having a second width d_{top} smaller than the first width, the second region being arranged substantially symmetrically on the outer region.
2. The apparatus of claim 1, wherein the substrate is a transparent medium having a first refractive index n_{WG} , and the diffractive elements have a second refractive index n_{element} greater than the first refractive index.
3. The apparatus of claim 1 or 2, wherein the first region is an outer region and the second region is an inner region extending inward from the outer region.
4. The apparatus of any one of claims 1-3, wherein the apparatus comprises a plurality of the diffractive elements arranged periodically as a reflective diffraction grating.
5. The apparatus of any one of claims 2-4, wherein the transparent medium is part of an optical waveguide.
6. The apparatus of any one of claims 1-5, configured to diffract light with a selected free-space wavelength λ_0 , wherein the second region has a height h_{top} substantially equal to $\lambda_0 / n_{\text{WG}}$.
7. The apparatus of any one of claims 1-5, configured to diffract light with a selected free-space wavelength λ_0 , wherein the first region has a height h_{bottom} substantially equal to $\lambda_0 / 2n_{\text{WG}}$.
8. The apparatus of any one of claims 1-7, wherein d_{bottom} is selected using

$$\sin(\gamma_q) - \sin\{(\theta' - \theta_{\text{inc}}^{\text{WG}})\} = q \frac{\lambda_{\text{WG}}}{d'}$$

$$\text{where } d' = \left(\left(\frac{d_{\text{bottom}} - d_{\text{top}}}{2} \right)^2 + h_{\text{top}}^2 \right)^{\frac{1}{2}}.$$

9. The apparatus of any one of claims 1-8, wherein d_{bottom} is selected using

$$d_{\text{top}} = \frac{1}{2} \frac{p\lambda_0}{n_{\text{WG}}(\sin \beta_p + \sin \theta_{\text{inc}}^{\text{WG}})}.$$

10. The apparatus of any one of claims 1-9, wherein d_{bottom} is in the range of 720-830nm.
11. The apparatus of any one of claims 1-10, wherein d_{top} is in the range of 200-240nm.
12. The apparatus according to any one of claims 1-11, wherein h_{top} is in the range of 390-480nm.
13. The apparatus according to any one of claims 1-12, wherein h_{bottom} is in the range of 180-195nm.
14. The apparatus according to any one of claims 2-13, wherein the transparent medium is at least a portion of a waveguide, and wherein a plurality of the diffractive elements are arranged periodically as a reflective diffraction grating configured to couple a second diffractive order of incident light into the waveguide.
15. A near-eye display comprising:
 - an image generator operative to generate an image; and
 - an apparatus according to any one of claims 2-14, wherein the transparent medium is a waveguide, and wherein the apparatus is operative to couple the image into the waveguide.
16. A method comprising:
 - directing light on a plurality of diffractive elements, wherein each diffractive element comprises:
 - a first region along an outer surface of a substrate, the first region being substantially rectangular in cross-section and having a first width d_{bottom} ; and
 - a second region extending from the outer region, the second region being substantially rectangular in cross-section and having a second width d_{top} smaller than the first width, the second region being arranged substantially symmetrically on the outer region.
17. The method of claim 16, wherein the substrate is a transparent medium having a first refractive index n_{WG} , and the diffractive elements have a second refractive index n_{element} greater than the first refractive index.
18. The method of claim 16 or 17, wherein the first region is an outer region and the second region is an inner region extending inward from the outer region.
19. The method of any one of claims 16-18, wherein the diffractive elements are arranged periodically as a reflective diffraction grating.

20. The method of any one of claims 16-19, wherein the transparent medium is part of an optical waveguide.
21. The method of any one of claims 16-20, wherein the light is light representing an image.

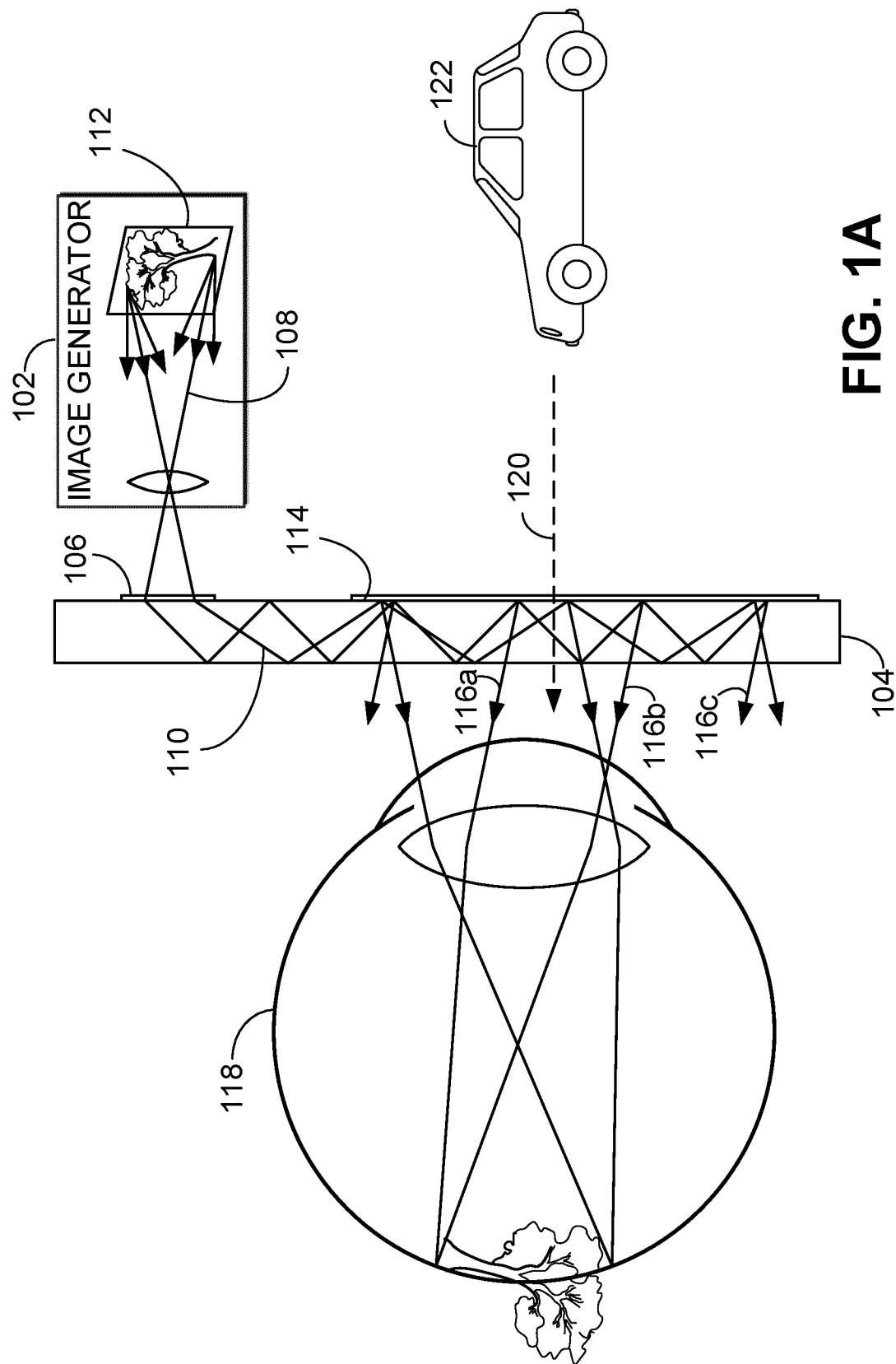


FIG. 1A

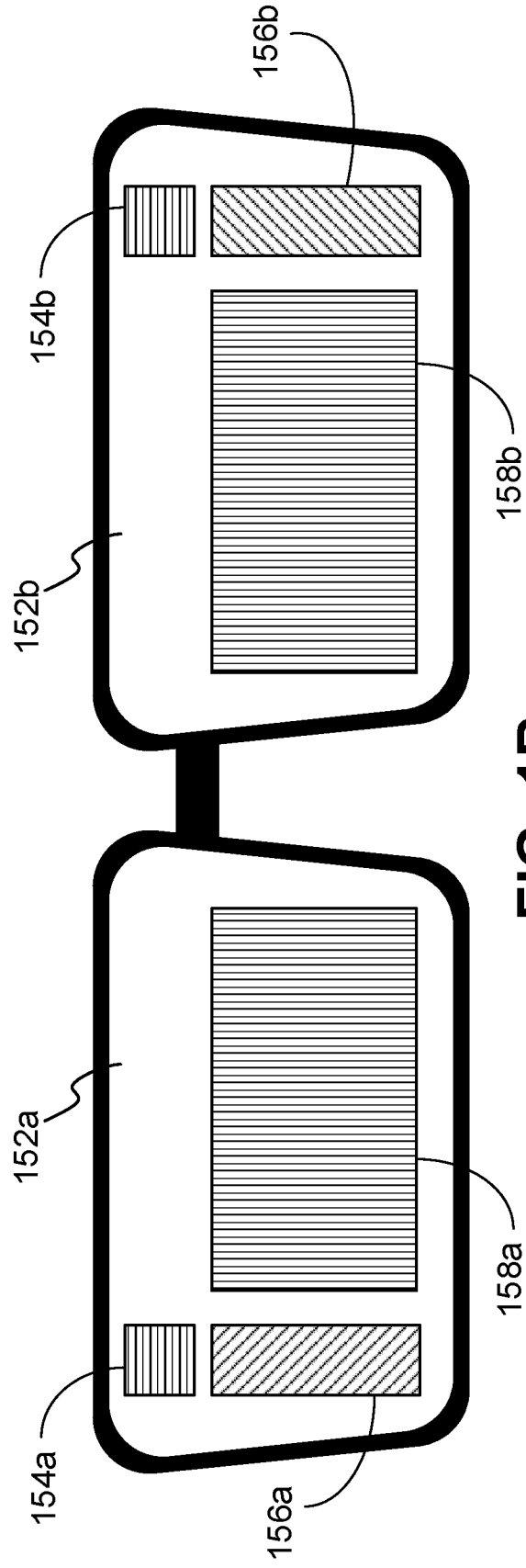


FIG. 1B

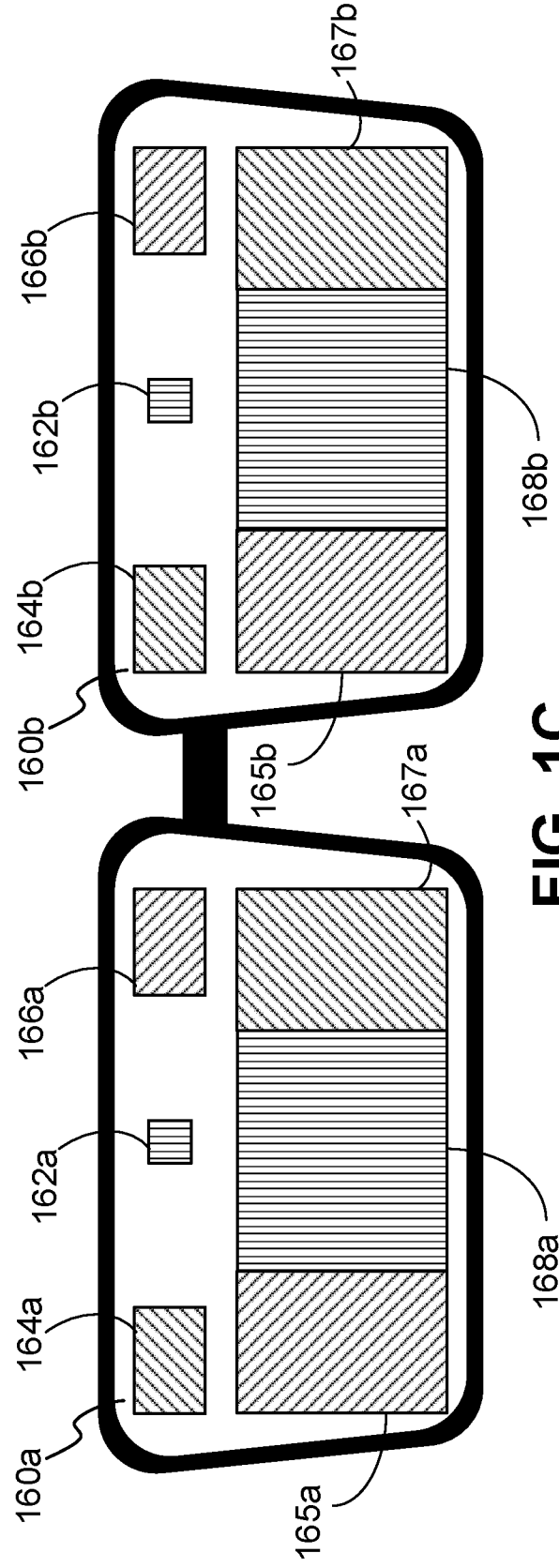


FIG. 1C

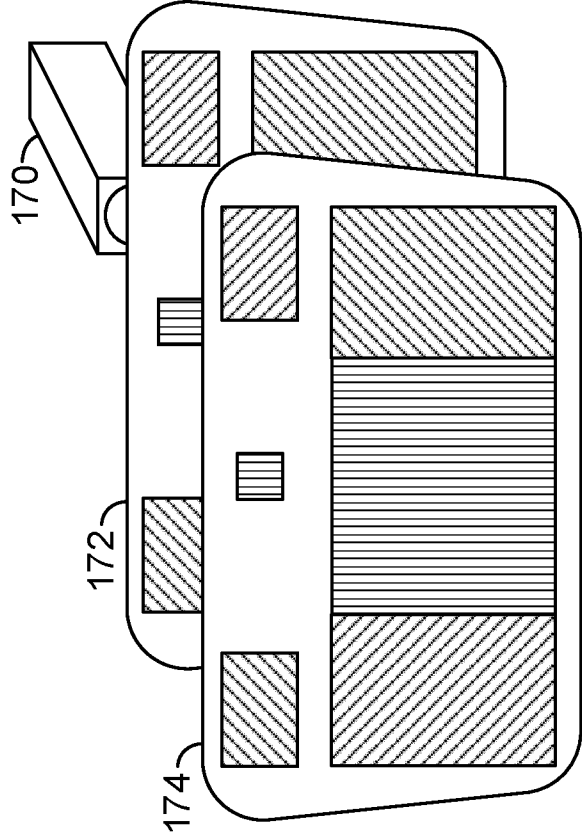


FIG. 1D

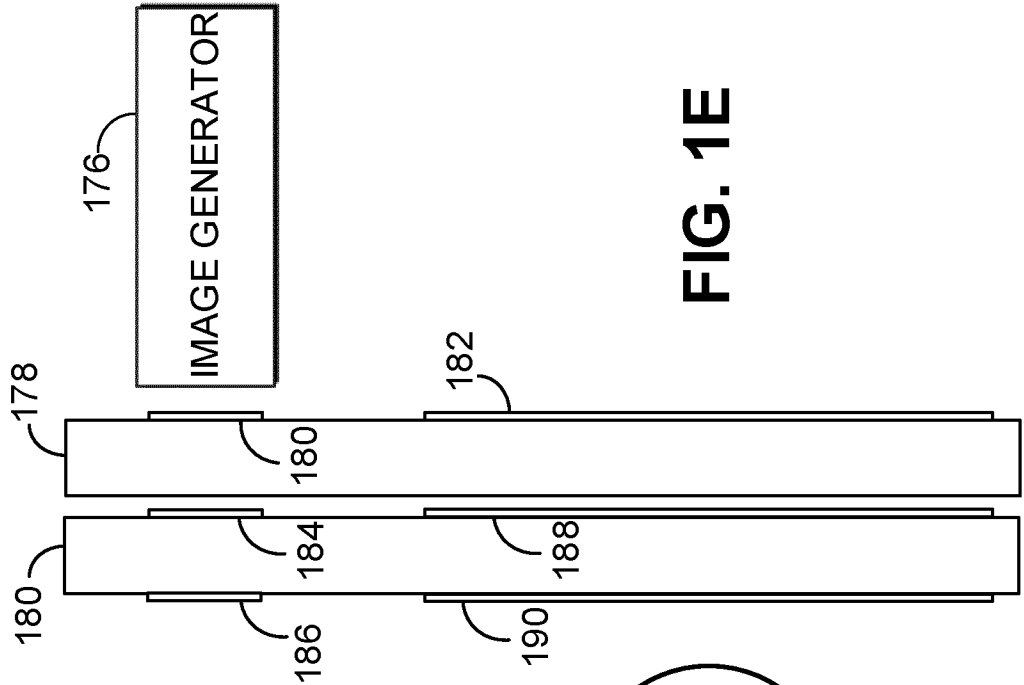


FIG. 1E

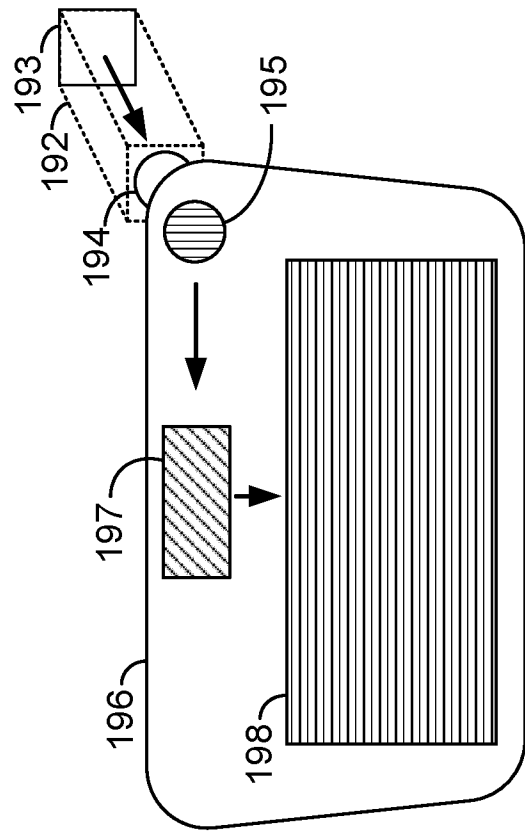


FIG. 1F

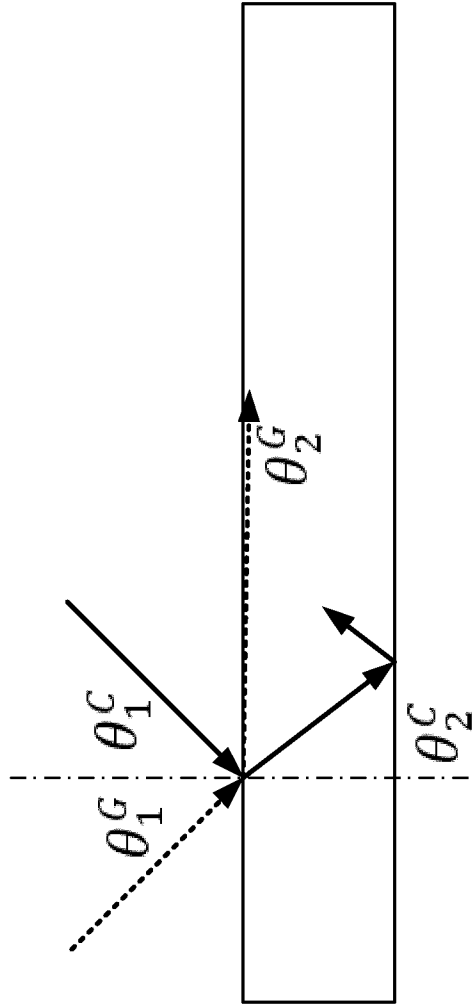


FIG. 2

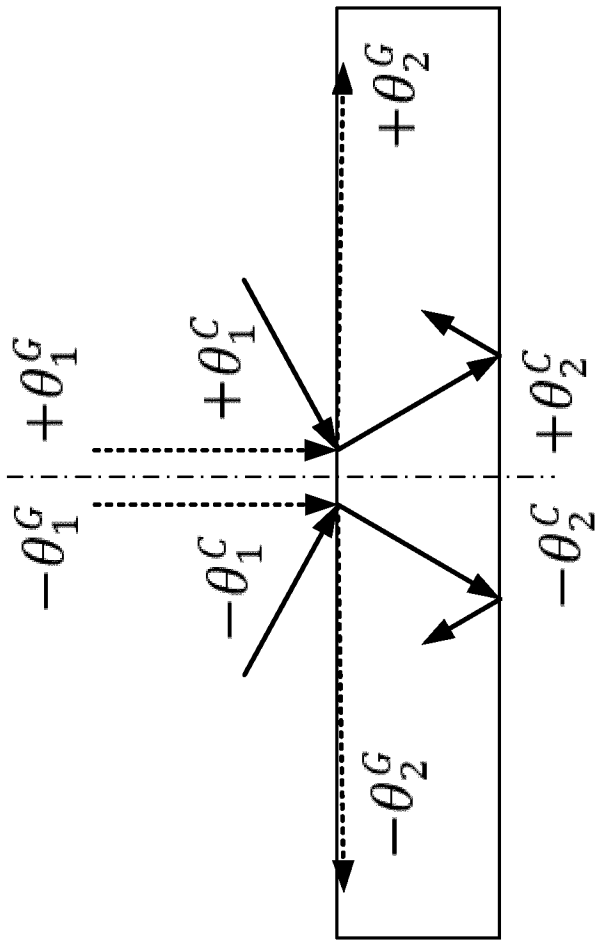
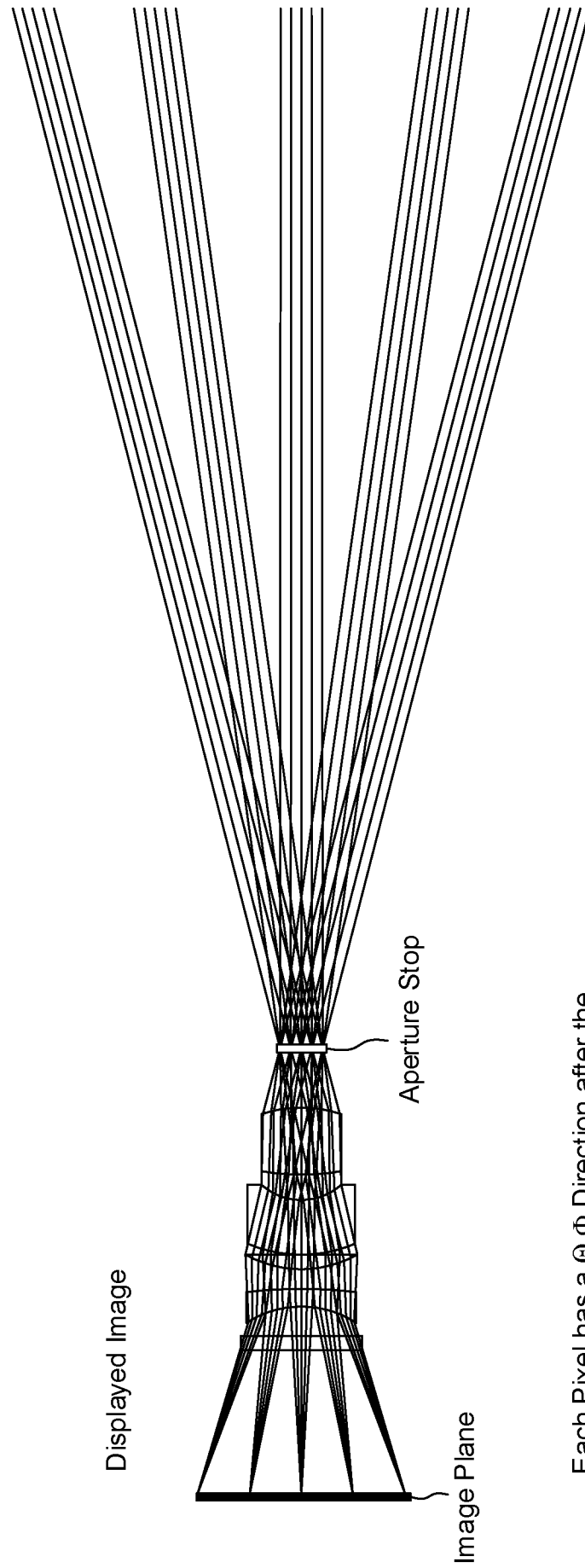


FIG. 3



Each Pixel has a Θ, Φ Direction after the Waveguide, this Direction Should be kept

FIG. 4

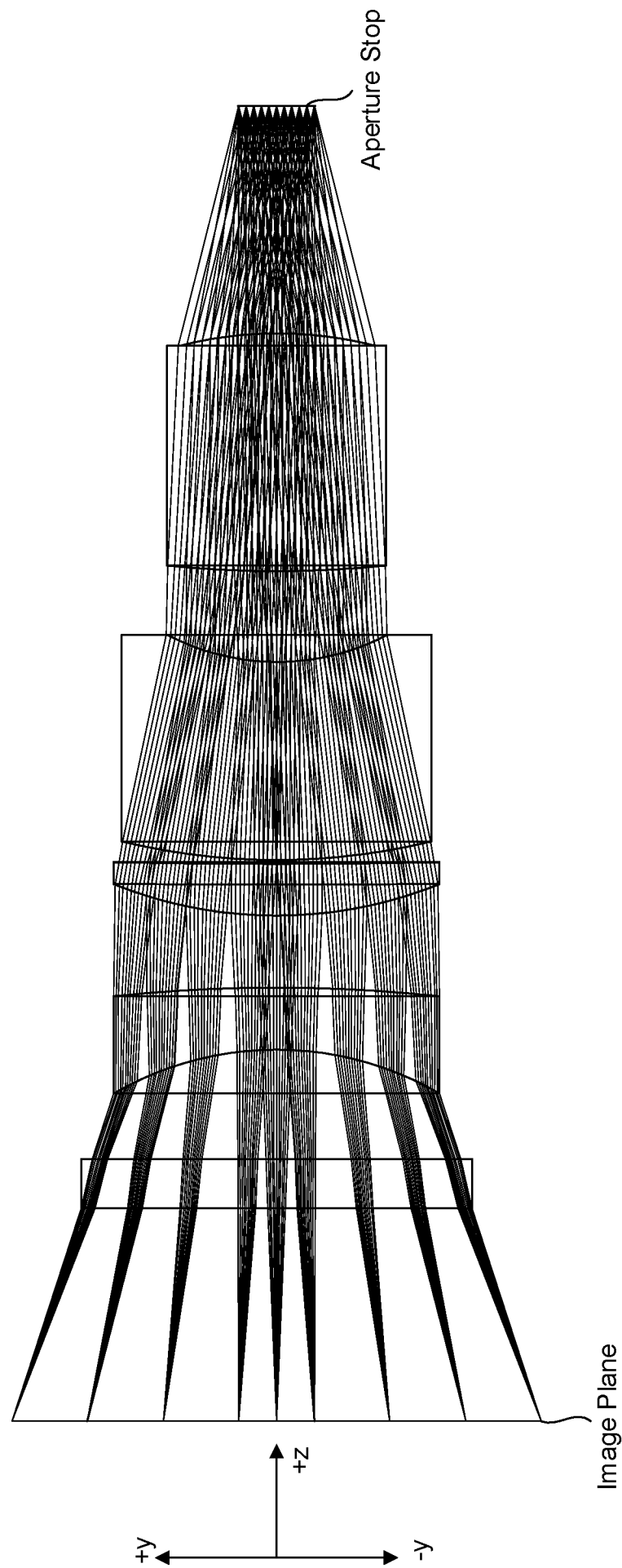


FIG. 5

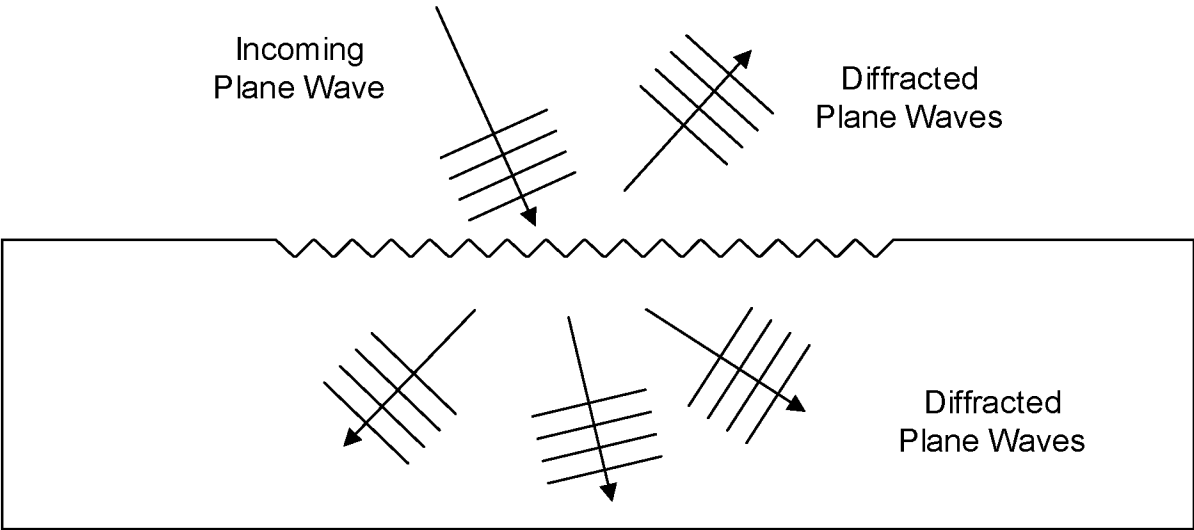


FIG. 6

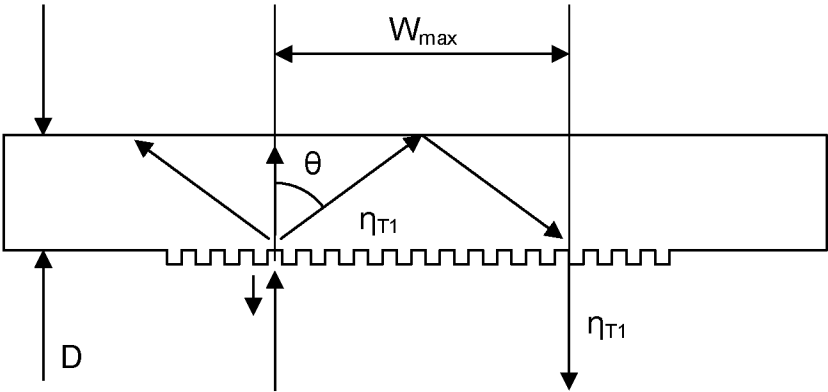


FIG. 7

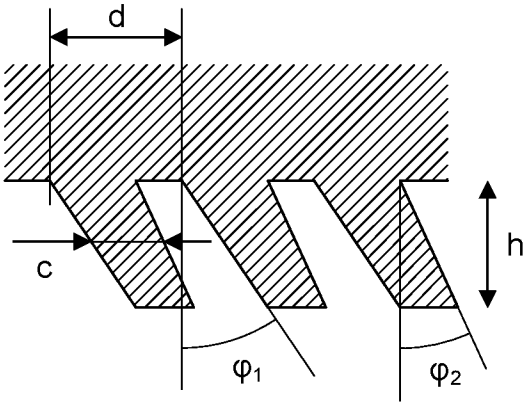
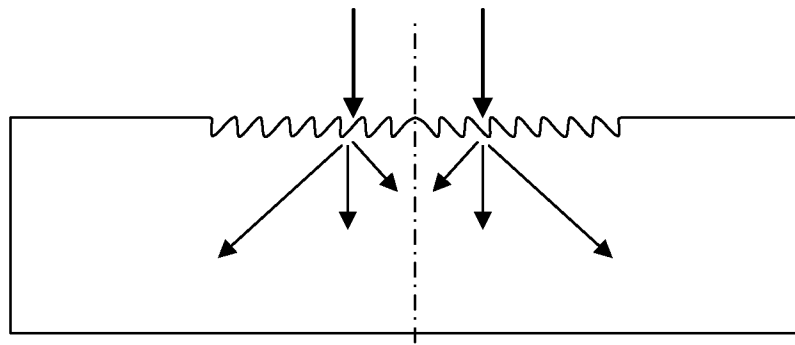
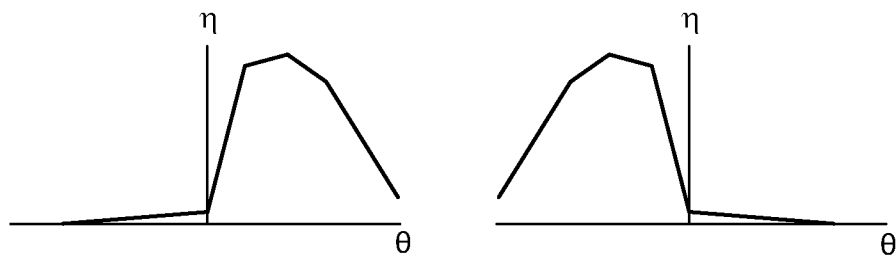
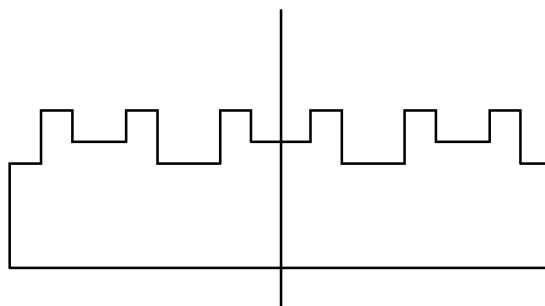
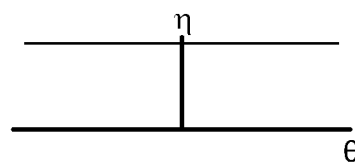


FIG. 8

**FIG. 9****FIG. 10****FIG. 11A****FIG. 11B**

$d_{\text{top}}=226\text{nm}$
 $h_{\text{top}}=425\text{nm}$
 $d_{\text{bottom}}=822\text{nm}$
 $h_{\text{bottom}}=191\text{nm}$
 $d=872.1\text{nm}$

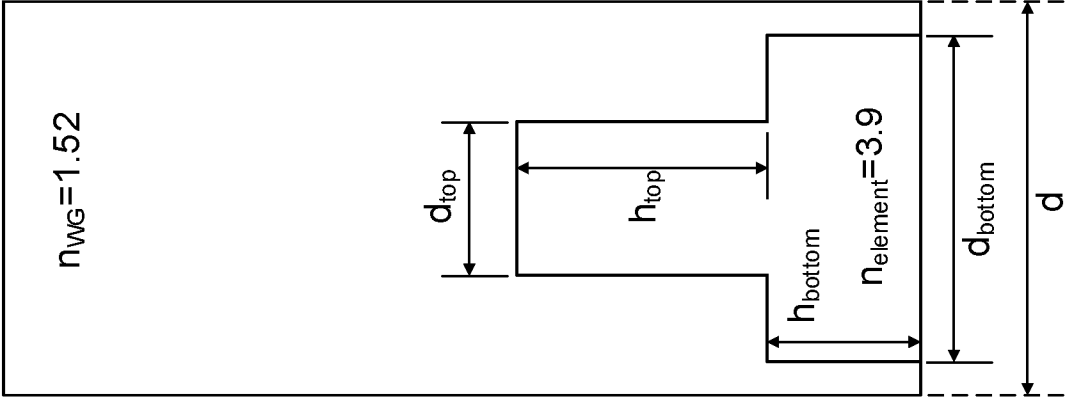


FIG. 12A

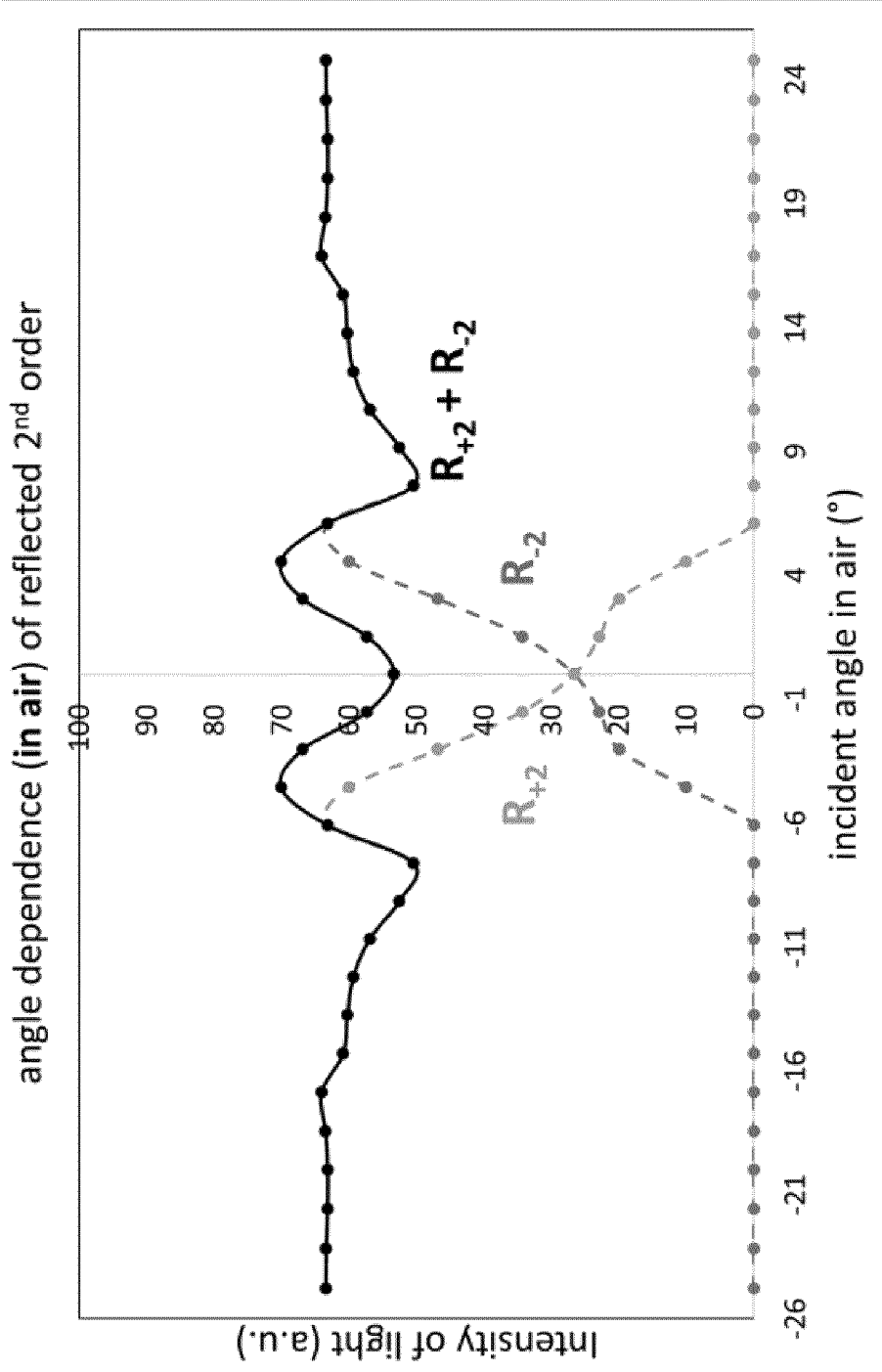
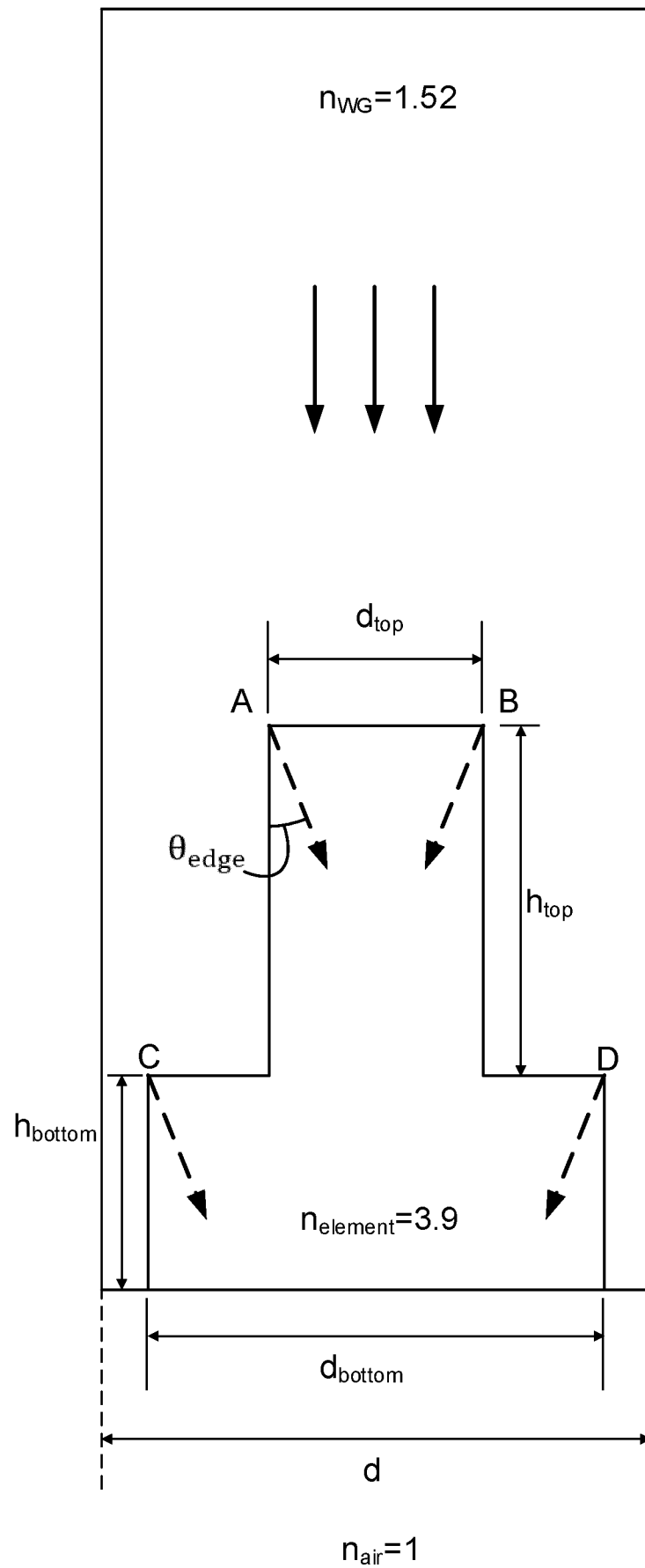


FIG. 12B

**FIG. 13**

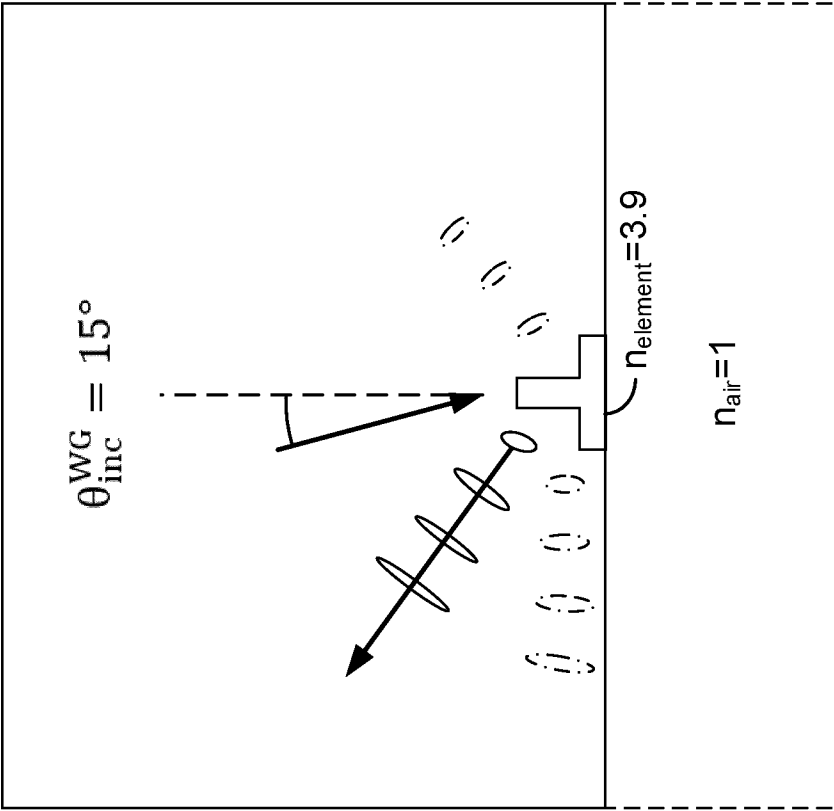


FIG. 14A

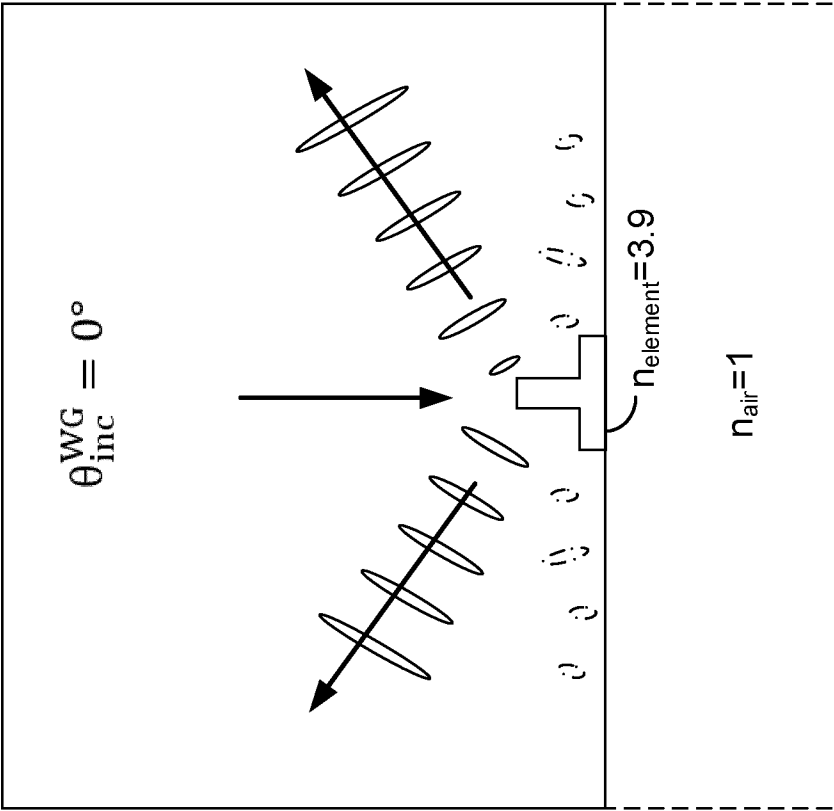


FIG. 14B

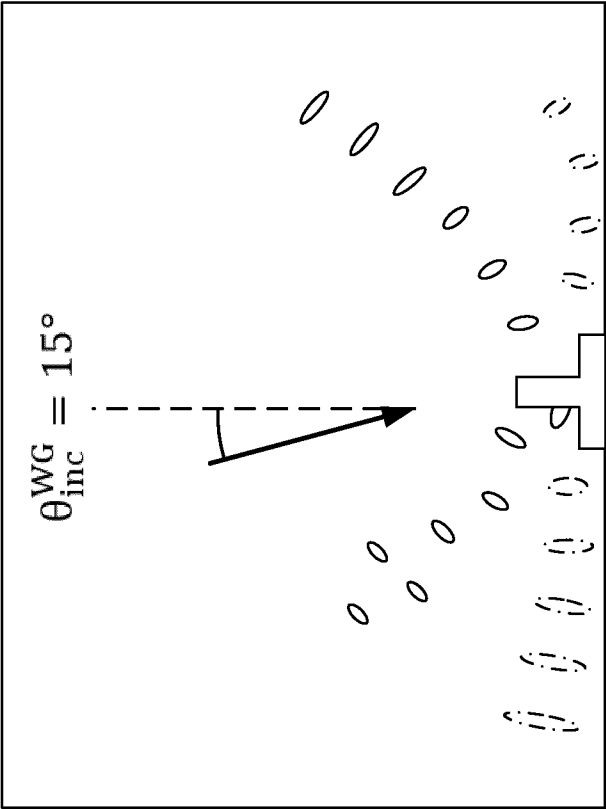


FIG. 15B

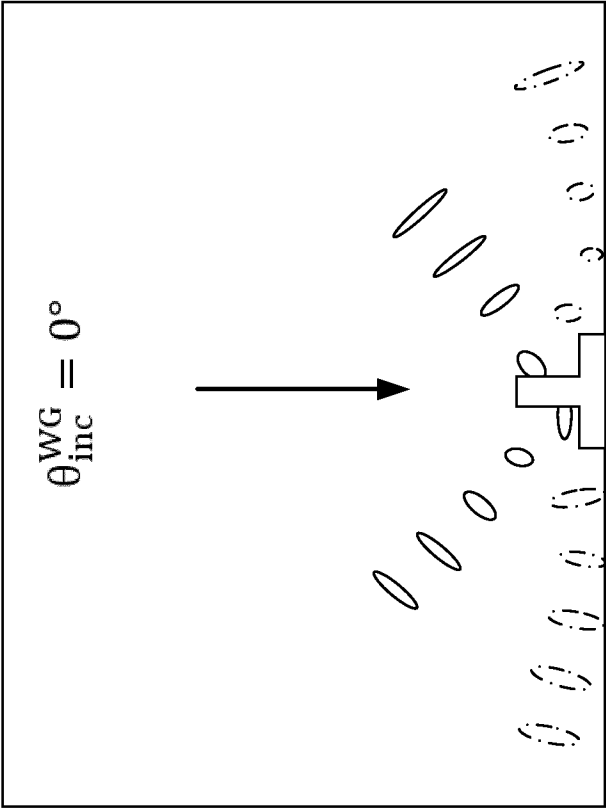


FIG. 15A

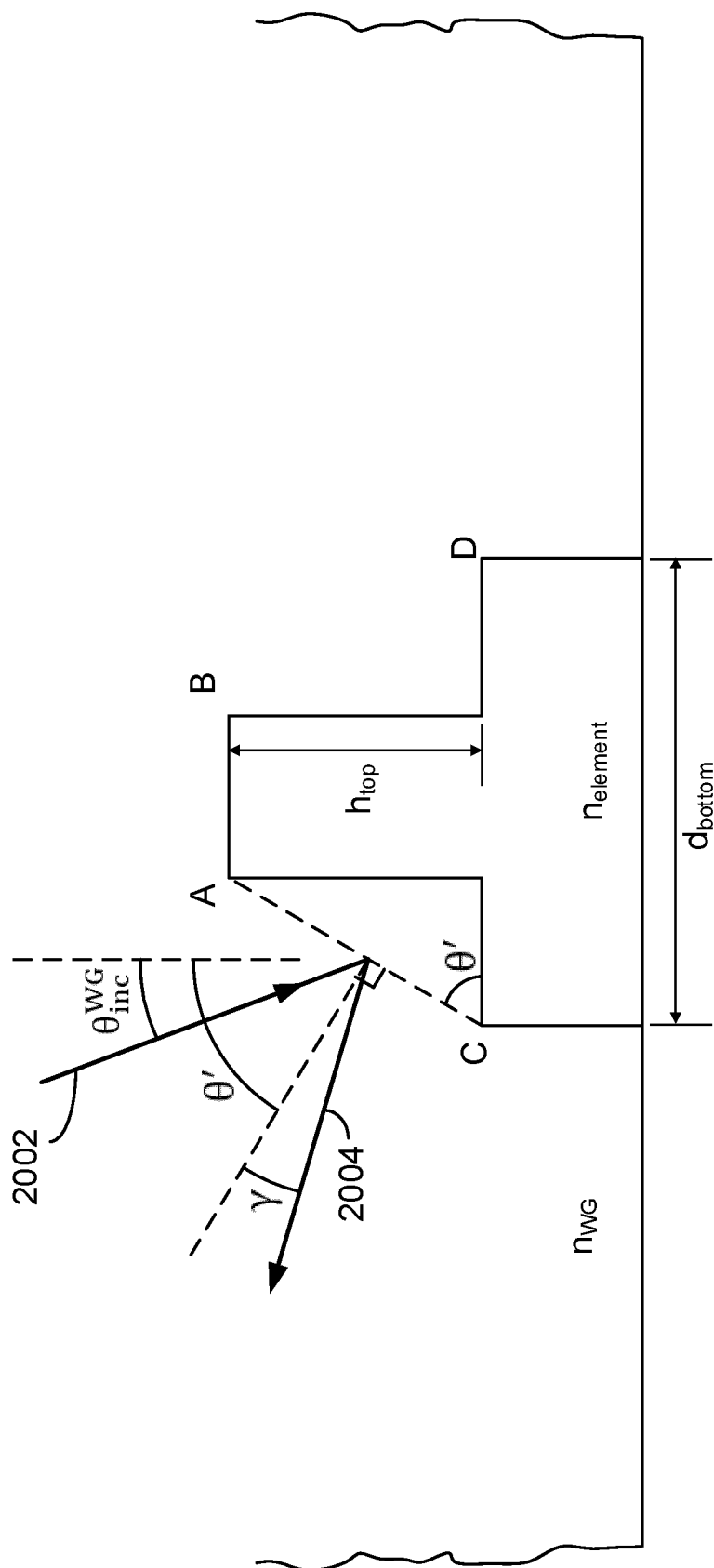


FIG. 16

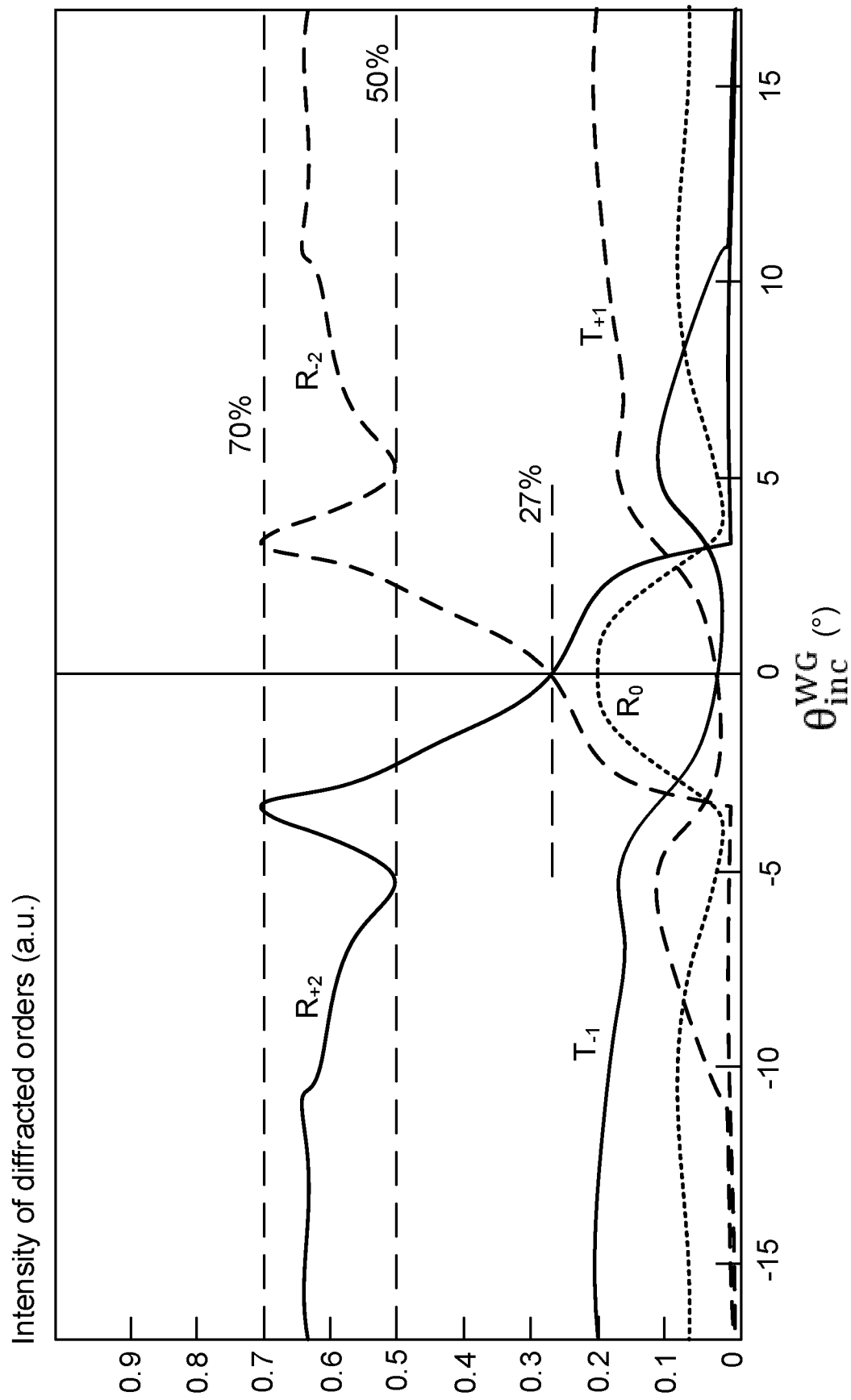


FIG. 17

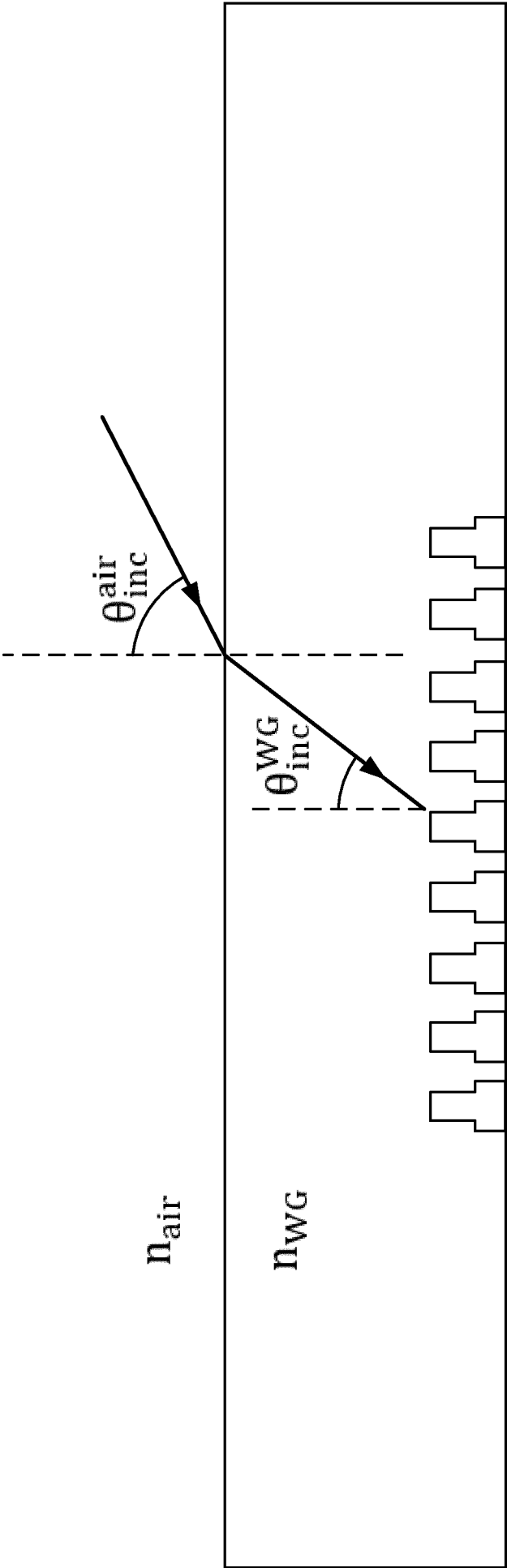


FIG. 18

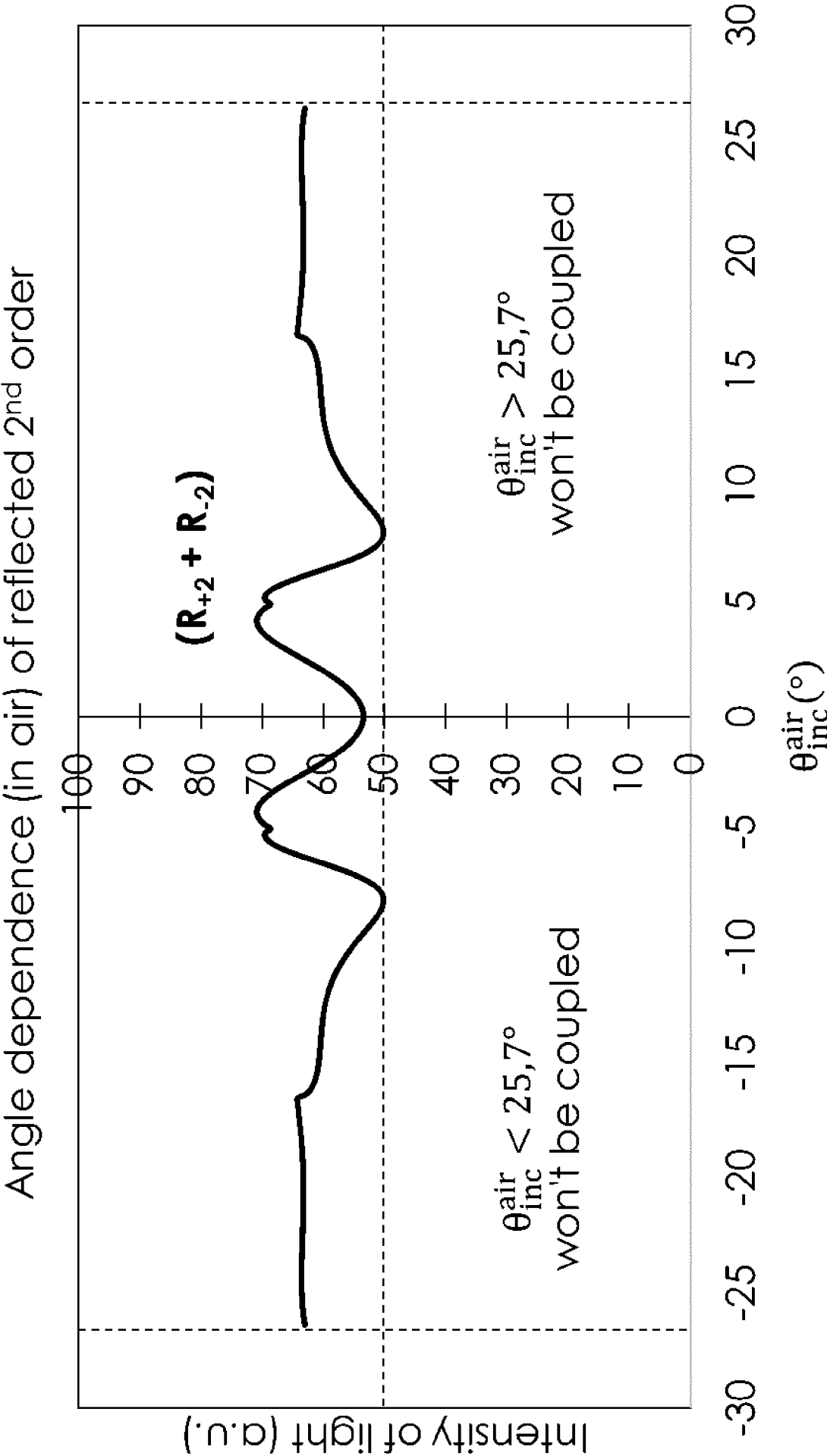


FIG. 19

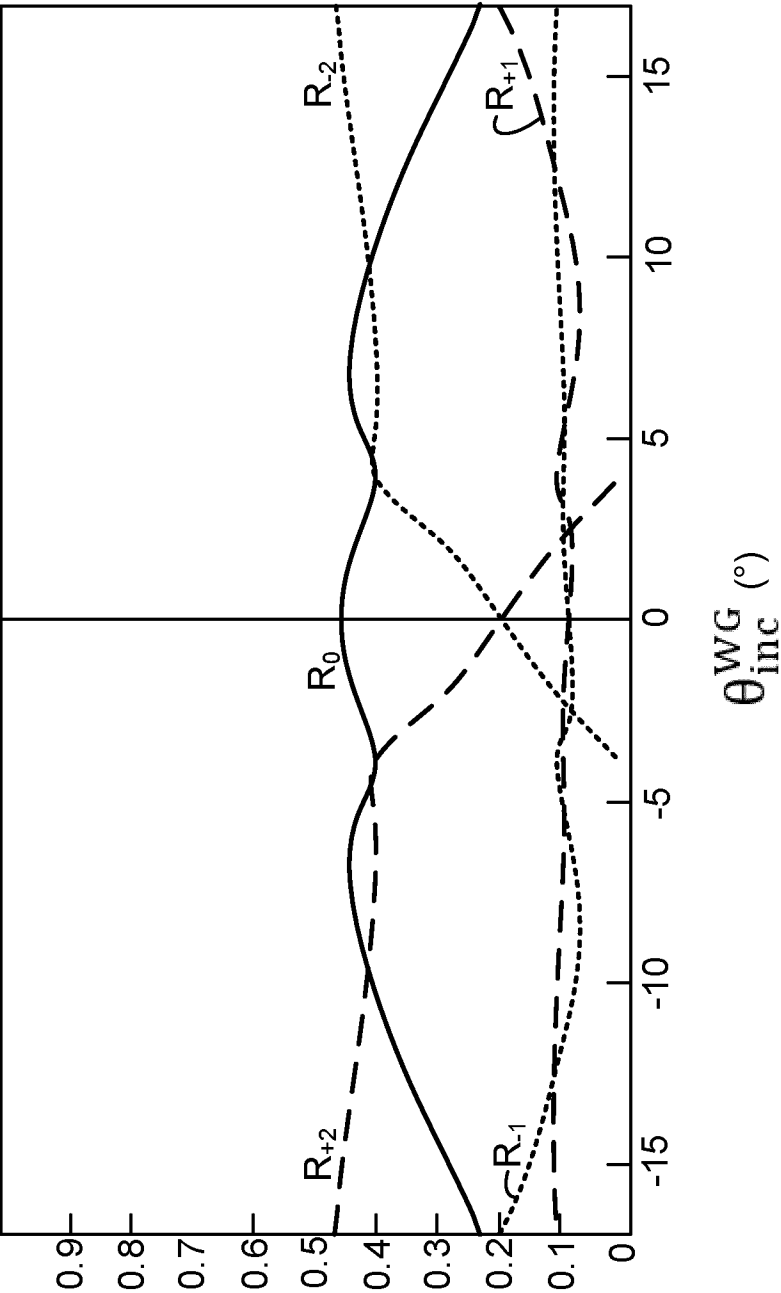


FIG. 20B

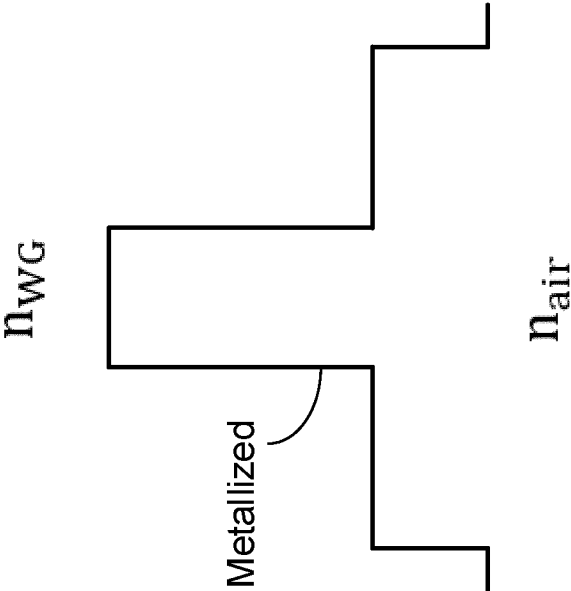


FIG. 20A

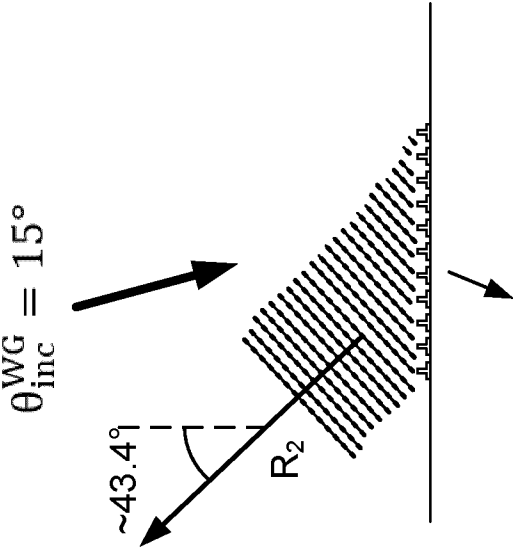


FIG. 21B

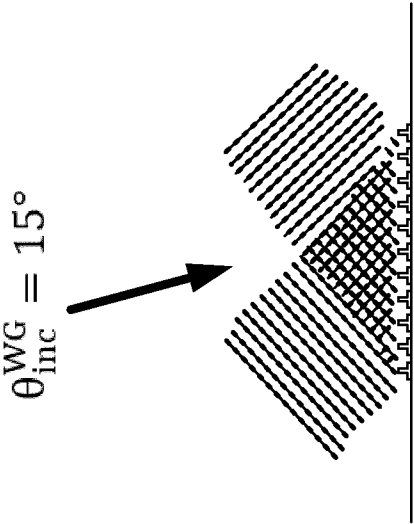


FIG. 21D

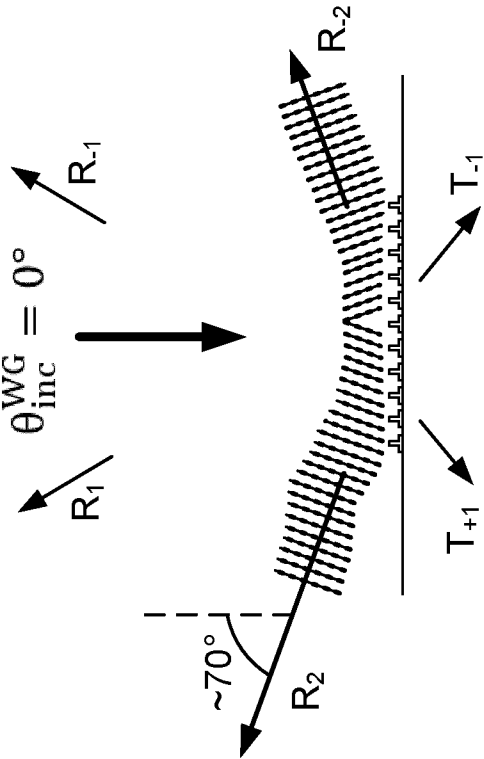


FIG. 21A

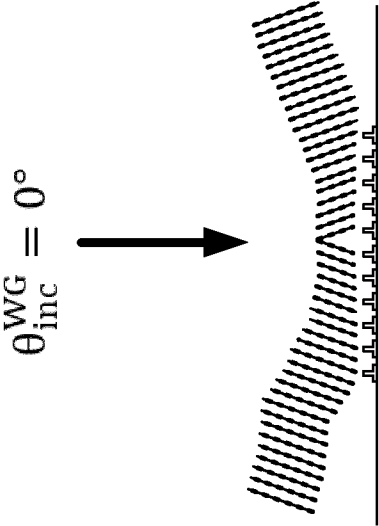
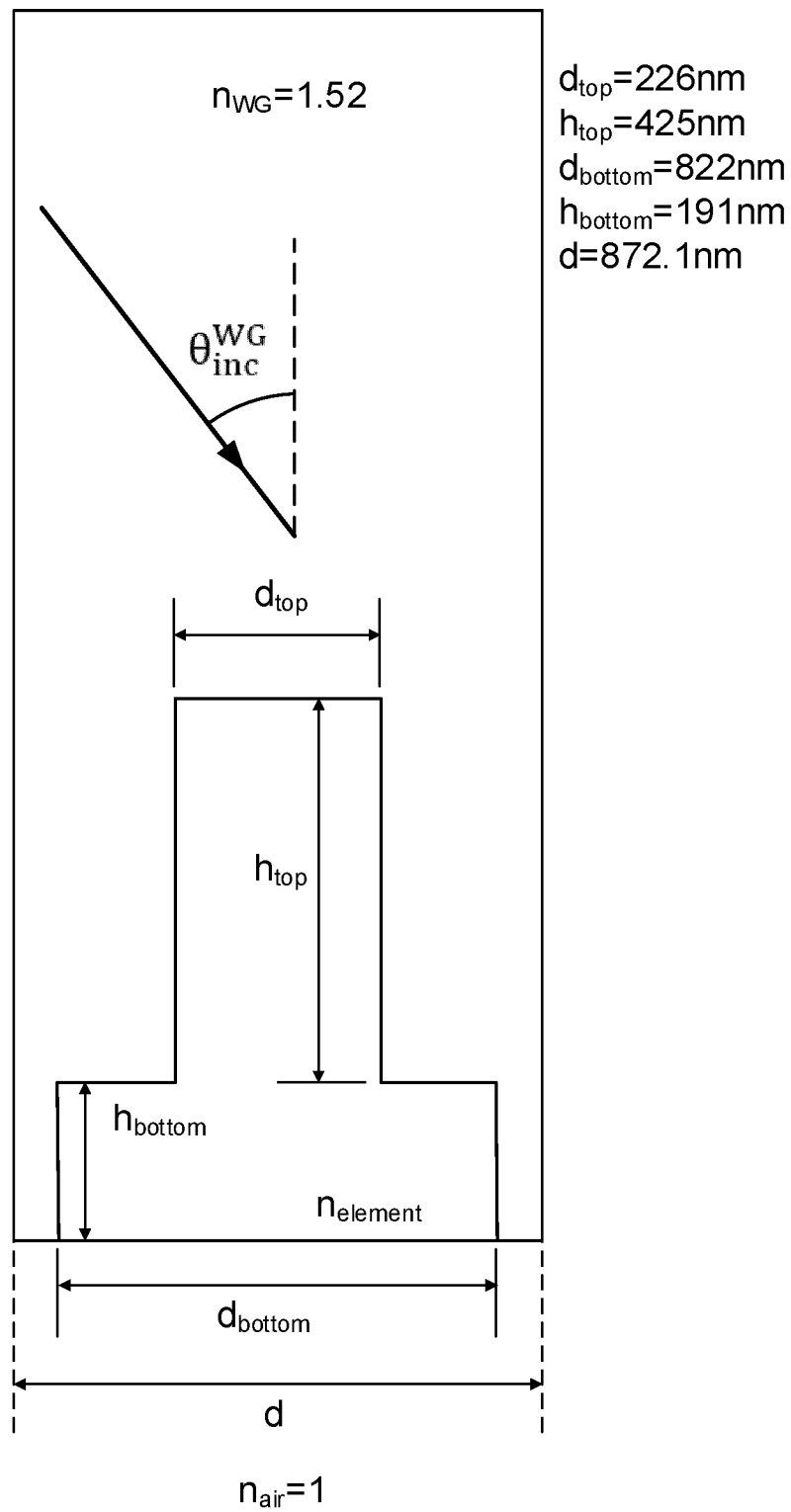


FIG. 21C

**FIG. 22**

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/068355

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B5/18 G02B27/00 G02B27/01
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2006/126179 A1 (LEVOLA TAPANI [FI]) 15 June 2006 (2006-06-15) abstract; figures 1,3 paragraph [0016] - paragraph [0084] paragraph [0098] - paragraph [0104] -----	1-21
X	US 2004/062502 A1 (LEVOLA TAPANI [FI]) 1 April 2004 (2004-04-01) abstract; figures 1,3 paragraph [0017] - paragraph [0043] paragraph [0056] - paragraph [0060] -----	1-21
X	EP 3 671 293 A1 (THOMSON LICENSING [FR]) 24 June 2020 (2020-06-24) abstract; figures 1,2,6,12 paragraph [0067] - paragraph [0071] paragraph [0085] - paragraph [0087] -----	1-21



Further documents are listed in the continuation of Box C.



See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

22 September 2021

Date of mailing of the international search report

06/10/2021

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Jakober, François

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2021/068355

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