

ASYMMETRIC GRATINGS FOR PARASITIC ORDER MITIGATION

BACKGROUND

Field

[0001] Embodiments of the present disclosure generally relate to waveguide combiners. More specifically, the present disclosure relates to asymmetric gratings for mitigating parasitic orders in diffractive waveguides.

Description of the Related Art

[0002] Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses that display a virtual reality environment that replaces an actual environment.

[0003] Augmented reality enables an experience in which a user can see through the display lenses of the glasses or other HMD device to view the surrounding environment while also seeing images of virtual objects that are generated for display and appear as part of the environment. Diffractive waveguide combiners are used in some augmented reality applications to transmit virtual images, graphics, and video that enhance or augment the environment that the user experiences.

[0004] Double-sided diffractive waveguides offer compact layouts and are often desired for various applications. However, such waveguides may struggle to achieve good color uniformity across a large field of view (FoV) due to the presence of unwanted "parasitic" diffraction transitions from combinations of grating vectors. These parasitic orders introduce loss, reducing the uniformity of outcoupled light across the FoV.

SUMMARY

[0005] According to one or more embodiments, an optical device includes a substrate, an input coupler disposed on a first surface of the substrate and configured to receive input light, a first output coupler disposed on the first surface of the substrate, a second output coupler disposed on a second surface of the substrate, wherein the first output coupler and the second output coupler comprise asymmetric

grating structures the first surface of the substrate opposes the second surface of the substrate.

[0006] According to one or more embodiments, an optical device includes a substrate, at least one underlayer disposed on the substrate, the at least one underlayer having a first refractive index (RI), grating structures disposed on the at least one underlayer, the grating structures comprising a first grating material having a second RI, and one or more encapsulation layers disposed on the grating layer, where a first encapsulation layer of the one or more encapsulation layers has a third RI, wherein the third RI is less than the second RI, and wherein the second RI is less than the first RI.

[0007] According to one or more embodiments, A method includes providing a double-sided grating structure having an input coupler (IC) and two expanding output couplers (EOCs), directing an input light through the IC, where the IC diffracts the input light into a first k-space distribution, expanding the first k-space distribution through the two EOCs to form a second, larger k-space distribution, reducing parasitic order transitions via one or more asymmetric grating structures included in at least one of the two EOCs,; and outputting, via at least one of the two EOCs, a wavefront having a field of view (FoV).

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

[0009] FIG. 1 is a schematic top view of a waveguide combiner according to embodiments described herein.

[0010] FIG. 2 is a schematic illustration of a double-sided grating architecture according to one or more embodiments described herein.

[0011] FIG. 3 is a K-Space diagram of double-sided grating with parasitic orders according to one or more embodiments described herein.

[0012] FIG. 4 is a K-Space diagram of mitigated parasitic orders in a double-sided or 2D grating according to one or more embodiments described herein.

[0013] FIG. 5 illustrates an asymmetrical grating cross-section according to embodiments described herein.

[0014] FIGS. 6A-6D illustrate various double-sided asymmetrical grating configurations according to one or more embodiments described herein.

[0015] FIG. 6E is an embodiment of a single-sided asymmetrical grating according to one or more embodiments described herein.

[0016] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0017] The present disclosure addresses the technical problem of parasitic diffraction orders that commonly afflict single-sheet waveguide combiners (also referred to herein as “waveguides” or “gratings”). In such systems, light propagates through the waveguide and encounters multiple grating interfaces, where it is diffracted multiple times. This multi-layer diffraction can result in unwanted light paths, known as parasitic orders, which degrade the quality of the signal by introducing noise and reducing the uniformity of the light output across the field of view (FoV). The presence of these parasitic orders particularly hampers the system's ability to maintain color fidelity and brightness uniformity, which are critical for high-resolution imaging applications and advanced display technologies.

[0018] One or more embodiments described herein relate to incorporating asymmetrically structured gratings into the waveguide design. These gratings include materials with different refractive indices and are shaped to impart a directional diffraction of light. By deviating from traditional symmetric grating structures, the asymmetric gratings enable the selective enhancement of desired (e.g., non-parasitic)

diffraction orders while simultaneously suppressing the parasitic orders. The gratings' asymmetry is carefully designed to create (induce) constructive interference (diffractions) in preferred directions—boosting the signal's strength—while causing (inducing) destructive interference (diffractions) in the directions where parasitic orders would emerge, thus mitigating their effect.

[0019] Furthermore, the grating materials are encased within encapsulation layers with carefully selected refractive indices to enhance this effect. The encapsulation, by having a lower refractive index than the grating materials, enables deeper, and therefore, more asymmetrically-diffracting grating structures without prohibitively increasing overall diffraction efficiency. Unencapsulated gratings deep enough to be strongly asymmetric would be too efficient and produce a uniformly bright display. This design allows for a more compact and efficient waveguide capable of producing a large FoV with improved color uniformity and brightness, overcoming the limitations of conventional double-sided diffractive waveguide systems.

[0020] FIG. 1 is a schematic top view of a waveguide combiner 100 according to embodiments described herein. It is to be understood that the waveguide combiner 100 described below is an exemplary waveguide combiner. The waveguide combiner 100 includes at least one of an in-coupler (IC) grating 102, an eye-pupil-expander (EPE) grating 104, an out-coupler (OC) grating 106, and a waveguide substrate 108. The waveguide substrate 108 has an edge 120. The IC grating 102 receives incident beams of light (a virtual image) from a microdisplay and directs the beams of light into the waveguide substrate 108. The incident beams of light undergo total-internal-reflection (TIR) and propagate in the waveguide combiner 100. The IC grating 102 directs many of the beams of light in the direction of the EPE grating 104 in order to direct the virtual image to the EPE grating 104. The incident beams of light continue under TIR and propagate in the waveguide combiner 100. The EPE grating 104 directs many of the beams of light in the direction of the OC grating 106 in order to direct the virtual image to the OC grating 106. The OC grating 106 out-couples the beams of light to the user in order to present the virtual image to the user. As the incident beams of light propagate in TIR in the waveguide combiner 100, some of the beams of light will be incident on the IC grating 102, the EPE grating 104, and the OC grating 106, while some of the beams of light will be incident on other areas of the waveguide substrate 108.

[0021] FIG. 2 is a schematic illustration of a double-sided grating architecture 200 according to one or more embodiments described herein.. In one or more embodiments, the double-sided grating architecture 200 includes a light engine 201, an input coupler (IC) 202, a substrate 203, a top expanding output coupler (EOC) 204 (also referred to herein as "EOC1" 204), and a bottom EOC 205 (also referred to herein as "EOC2" 205) disposed on the top and bottom sides of the substrate 203. The light engine 201 generates the light that will be manipulated by the optical system. The light engine 201 could include, for example, a laser diode or LED source that produces the initial beam of light. The IC 202 typically consists of a diffractive grating designed to match the incoming light's wavefront and direct the light into the substrate 203 at the required angle for total internal reflection (TIR). The substrate 203 is the material through which the light travels. The substrate 203 is designed to support TIR, keeping the light contained within the substrate 203 by reflecting the light internally at the interface between the substrate 203 and the surrounding medium, which typically has a lower refractive index. The role of the substrate 203 is to guide the light between the IC 202 and the top EOC 204 and the bottom EOC 205 while maintaining TIR conditions. The refractive index of the substrate 203 is higher than that of the surrounding environment to ensure the light reflects internally. In one or more embodiments, the substrate 203 is a highly transparent material, such as clear glass or quartz.

[0022] In one or more embodiments, EOC1 204 and EOC2 205 are grating structures that gradually expand the light as the light propagates through the substrate 203. EOC1 204 is situated on the top side of the substrate 203 and expands and couples the light out of the substrate 203. Similar to EOC1 204, EOC2 205 is situated on the bottom side of the substrate 203 and expands and couples the light out of the substrate 203. EOC1 204 and EOC2 205 serve as outcouplers, extracting the light from the substrate 203 and directing the light towards the viewer's eyes or another target. The expansion effect is necessary to support the entire field of view (FoV) over an eyebox region to accommodate all users' eye positions.

[0023] Parasitic orders in a diffractive optical system are typically unwanted diffraction modes that occur due to the inherent properties of the diffraction gratings used to manipulate light. Parasitic orders arise from the grating equation, which

describes the angles at which light of a given wavelength will be diffracted when it encounters a grating. In one or more embodiments, the grating equation is:

$$m\lambda = d(\sin \theta_i + \sin \theta_m)$$

[0024] where m is the order of diffraction, λ is the wavelength of the light, d is the grating period (the distance between adjacent grating lines), θ_i is the angle of incidence of the light on the grating, and θ_m is the angle of the m -th order diffraction.

[0025] Diffractive gratings can produce multiple orders of diffraction (where m can be 0, ± 1 , ± 2 , ...). While the $+1$ and -1 orders might be used for the intended optical path, the higher orders (± 2 , ± 3 , ...) are typically not desired and can interfere with the image quality. Any imperfections or variations in the grating period or shape can cause additional diffraction peaks, leading to parasitic light paths. In a complex optical system like the one described, where there are multiple diffractive elements (such as the IC 202, EOC1 204, and EOC2 206), the interaction between these elements can lead to the generation of new, undesired diffraction orders that may be supported by a substrate of sufficiently high refractive index. Different wavelengths of light diffract at different angles. If a grating is designed to diffract one wavelength optimally, other wavelengths might be diffracted into parasitic orders. The efficiency of a grating can also depend on the polarization of the incident light, which might lead to certain polarizations being diffracted into parasitic orders.

[0026] To mitigate parasitic orders, the grating structures are designed with characteristics, including but not limited to, the periodicity and orientation of the gratings, to favor the desired diffraction orders while suppressing the parasitic orders. Asymmetrical grating designs can preferentially enhance the efficiency of certain diffraction orders over others. By designing the grating lines with an asymmetric profile (not symmetrical across the plane perpendicular to the substrate surface), the grating efficiency for the undesired orders can be reduced. This asymmetry can cause destructive interference for the parasitic orders while constructive interference enhances the desired orders. Unencapsulated gratings (or grating structures) that are sufficiently deep to diffract asymmetrically have too high an efficiency to achieve a uniform display across the waveguide field of view and eyebox. Encapsulation of the asymmetric gratings with a lower-index material reduces the refractive index

contrast, and therefore the overall grating diffraction efficiency, without reducing the asymmetry.

[0027] FIG. 3 is a k-space (momentum space) diagram 300 of an optical system with a double-sided grating, such as the optical system in FIG. 2. A k-space diagram, also known as a reciprocal space diagram or momentum space diagram, is a graphical representation used to visualize the relationship between different wavevectors in an optical system. In the context of waveguide grating, the k-space diagram is used to visualize the relationship between grating vectors, which in turn helps to understand and control the behavior of the diffracted light.

[0028] Grating vectors are used to describe the behavior of light as it interacts with periodic structures like diffraction gratings. Mathematically, grating vectors (G) can be represented as: $G = m \times (2\pi/\Lambda)$, where m is the diffraction order (an integer), Λ is the grating period (the distance between repeating elements in the grating), and $2\pi / \Lambda$ represents the spatial frequency of the grating. By carefully selecting grating vectors and studying their interactions in the k-space diagram, it is possible to design gratings that minimize or eliminate unwanted parasitic orders, leading to improved performance in double-sided diffractive waveguides.

[0029] Embodiments of the k-space diagram 300 in FIG. 3 include a solid annular ring 301 in which the grating vectors are supported by substrate through total internal reflection. These vectors represent the directions of the diffracted light that remains guided within the substrate due to total internal reflection. Outside of the annular ring 302 is the area that grating vectors are not supported by the substrate 203. These vectors within the inner annulus boundary represent directions of diffracted light that will escape the substrate and propagate into the surrounding air. Vectors outside the outer annulus boundary represent diffracted orders not supported by the substrate or air.

[0030] The different shadings of blue, green, and red 303a - 303c indicate the regions of k-space that correspond to different colors within the device's field of view (FoV). Each color has its own set of grating vectors due to the differing wavelengths of the colors. In various embodiments, one goal is to have these different color regions move along the paths indicated by the arrows without diffracting to higher orders and

with minimal encounters with the annular boundary to create a combined image in the visible spectrum with good color uniformity. If there are interactions with boundaries or higher diffractive orders, color fringing or poor image quality can occur.

[0031] In the k-space diagram 300, the desired transitions are indicated by the shaded arrows, while the undesired mitigated transitions and parasitic orders are indicated by the unshaded arrows. The shaded arrows point from the IC 202 to the EOCs 204 and 205, illustrating the intended path of light through the system. A "desired transition" refers to the spatial frequencies that the grating is designed to couple in, expand, and couple out efficiently. These transitions result in the constructive interference of light in the intended directions, which is necessary for the device to function as intended. For example, in a display device, the desired transitions would ensure that the viewer sees the image with the correct brightness and full field of view at all colors across the eyebox.

[0032] A "mitigated undesired transition" refers to spatial frequencies that are not the primary target of the diffraction grating but are a byproduct of the grating design. Mitigated undesired transitions are indicated by unshaded arrows in the k-space diagram. In optical systems, undesired transitions can lead to artifacts, such as ghost images, stray light, or reduced contrast, and efficiency in the intended image. Although these transitions cannot always be completely avoided, their impact is minimized.

[0033] Parasitic orders are highlighted with dashed outlines and are the diffraction orders that are not desired but are still at least partially supported by the substrate (Total Internal Reflection, TIR). These parasitic orders can result in color nonuniformities at the output of the waveguide combiner.

[0034] FIG. 4 provides a k-space diagram 400 and accompanying mathematical expressions outlining the wave vector relationships for an optical system with diffractive elements such as gratings. The diagram illustrates the k-space with axes k_x parallel (k_0) and k_y parallel (k_0). The large circle 401 represents the light cone in the substrate 203, within which guided modes can exist.

[0035] Within the k-space diagram 400, k_{IC} , k_{EOC1} , and k_{EOC2} are the wave vectors for the input and output couplers. The square symbols indicate different wave vector components or combinations that arise due to the presence of multiple gratings. The

annulus with outer radius n_{sub} represents the light cone in the substrate 203, indicating the limit for guided modes within the material based on its refractive index n_{sub} . Only wave vectors that lie within this annulus can propagate within the substrate; any vectors within the inner annular boundary would correspond to modes that are not guided and thus are lost to the surrounding medium. Vectors outside the outer annular boundary correspond to modes not supported by the substrate or the surrounding medium. The circles highlighted with dotted lines show locations of allowed transitions, prohibited parasitic orders, and mitigatable (but undesired) parasitic orders.

[0036] Allowed transitions are seeking to ensure that the wave vectors k_{allow} that represent allowed transitions are within the radius defined by the substrate refractive index n_{sub} , i.e., k_{allow} should be lower than n_{sub} to be supported by the system. The following equations describe how these allowed transitions are formed:

- a) $k_{allow} = k_{FoV} + k_{IC}$: The allowed k-vector is the sum of the field of view's wave vector and the input coupler's wave vector.
- b) $k_{allow} = k_{FoV} + k_{EOC1,2}$: The allowed k-vector is also the sum of the field of view's wave vector and the expanding output couplers' wave vectors.

[0037] Prohibited parasitic orders are k-vectors that are undesirable and ideally should be larger than n_{sub} to fall outside the light cone in the substrate, thus not being guided modes. The following equations describe conditions that generate prohibited orders:

- a) $k_{para} = k_{FoV} + m \cdot k_{IC} - n \cdot k_{EOC1,2}$: Parasitic wave vectors generated when m times the input coupler's wave vector and n times the expanding output couplers' wave vectors subtract from the field of view's wave vector.
- b) $k_{para} = k_{FoV} + n \cdot k_{IC}$: Parasitic wave vectors resulting from n times the input coupler's wave vector added to the field of view's wave vector.
- c) $k_{para} = k_{FoV} + n \cdot k_{EOC1,2}$: Parasitic wave vectors generated from n times the expanding output couplers' wave vectors added to the field of view's wave vector.

[0038] Where $n \in \text{integers} > 1$, $m \in \text{integers} > 0$.

[0039] Mitigatable (but undesired) parasitic orders are parasitic orders that can potentially be mitigated, although they are unwanted. The mitigatable parasitic orders are represented by the following equations:

a) $k_{\text{para-mit}} = k_{\text{FoV}} + k_{\text{IC}} + n \cdot k_{\text{EOC1,2}}$: A mitigatable parasitic k-vector is the sum of the field of view's wave vector, the input coupler's wave vector, and n times the expanding output couplers' wave vectors. These should also be designed to fall outside the light cone in the substrate.

[0040] In various embodiments, one goal of the disclosed architecture is to ensure that the allowed transitions are within the substrate's light cone, making the transitions effective for the optical system's operation, while the parasitic orders are outside of the light cone, either prohibited entirely or mitigated as much as possible.

[0041] The mitigation of parasitic orders in this context refers to the design and structuring of the grating vectors such that undesired diffracted orders are minimized. This mitigation can be achieved through various means, including: (i) selection of the grating periods and angles to ensure the parasitic orders are not, or only, minimally supported by the substrate's total internal reflection (TIR), (ii) engineering the substrate and surrounding media's refractive index to promote TIR for desired orders and prevent propagation of undesired ones, and (iii) utilizing asymmetric geometric or material dispersive properties to strongly diffract desired orders while dispersing or only weakly diffracting parasitic orders.

[0042] FIG. 5 illustrates a cross-sectional view of an asymmetrical grating 500 according to embodiments described herein. In one or more embodiments, the asymmetrical grating 500 includes grating structures 501 that are asymmetric. Although, the embodiment of the asymmetrical grating 500 in FIG. 5 shows grating structures 501 that are asymmetric and have specific geometric shapes, the grating structures 501 can be of any geometric shape. The asymmetry here refers to one or more of grating structures 501 having asymmetrical geometric shapes, asymmetrical periodicities along different directions, or asymmetrical material compositions.

[0043] For example, embodiments of the grating structures 501 may have non-uniform shapes, unlike traditional symmetric grating structures with consistent groove shapes. Embodiments of the grating structures 501 may comprise slanted gratings, blazed gratings, or multi-dimensional gratings

[0044] The grating structures 501 may have different periodicities in different light propagation directions, such as periodicity (Λ_x , Λ_y) in the direction of two different axes (e.g., the x-axis and the y-axis) in x and y directions. The periodicity of the grating structures 501 is designed to manipulate the phase of incident light in different directions.

[0045] The grating structures 501 may be made from one or more grating materials. For example, the grating materials may be formed from a grating material 1 501a (also described herein as the “first grating material 501a”) and a grating material 2 501b (also described herein as the “second grating material 501b”). Although the grating structures 501 are described as being formed by two different grating materials, the gratings structures 501 may be formed by one grating material or any other quantity of grating materials.

[0046] The first grating material 501a and the second grating material 501b are two different grating materials used to form the grating structures 501. The first grating material 501a and the second grating material 501b are chosen based on their refractive indices, transparency at operational wavelengths, and other optical properties that influence the diffraction and propagation of light through the grating. Possible gratings materials can include, but are not limited to, oxides, resists, polymers, metals, other dielectrics, etc. Real refractive index values can include, but are not limited to, refractive index values greater than 1, such as 1.1, 1.5, 1.7, 2.0, 2.3, etc. In various embodiments, the cross-sectional grating dimensions can be smaller than the wavelengths of visible light <400 nm, and the grating lines can be the length of the grating region, for example, on the millimeter (mm) to centimeter (cm) scale.

[0047] In some embodiments, the first and second grating materials 501a and 501b have different refractive indices. In various embodiments, the first grating material 501a and the second grating material 501b are not stacked in horizontal

layers or aligned in vertical slices, but are stacked in an angled direction. This asymmetrical grating material configuration would affect the phase velocity of light traveling through the first and second grating materials 501a and 501b in different directions. In some configurations, the first grating material 501a might be a core material that forms the main body of the grating, influencing the primary diffraction characteristics. The second grating material 501b might be a cladding or modulation material that adjusts or fine-tunes the diffraction, perhaps adding a second-order modulation to the grating or altering the propagation modes within the grating.

[0048] In some embodiments, the grating structures 501 may be encapsulated by dielectric materials with different refractive indices. The grating structures 501 may be encapsulated by one layer of dielectric material with one refractive index. The grating structures 501 may also be encapsulated by two or more layers of dielectric material with two or more refractive indices, such as encapsulation 1 503 (also described herein as a “first encapsulation layer 503”) and encapsulation 2 504 (also described herein as a “second encapsulation layer 504”) in FIG. 5. Encapsulating the grating structures 501 shields the grating structures 501 from environmental factors such as moisture, dust, and mechanical wear. Accordingly, encapsulation may be implemented to maintain the integrity and performance of the optical device (waveguide combiner) over time. The material chosen for encapsulation layer(s) may be selected to match the refractive index of the grating material to minimize any unwanted reflections or refractions that could affect the performance of the device.

[0049] The grating structures 501 and the encapsulation layers may be disposed on one or more underlayers disposed over a substrate 507. The one or more underlayers may include, but are not limited to, underlayer 1 506 (also described herein as a “first underlayer 506”) and underlayer 2 505 (“also described herein as a “second underlayer 505”). The one or more underlayers (e.g., the first underlayer 506 and the second underlayer 505) are optional and any quantity of optional underlayers may be disposed over the substrate 507. For example, the first underlayer 506 is disposed over the substrate 507, the second underlayer 505 is disposed over the first underlayer 506. Stated differently the first and second underlayers 506 and 505 are positioned beneath the grating structures 501 and above the substrate 507. The first and second underlayers 506 and 505 act as an optical interface between the substrate 507 (the stable base) and the grating structures 501. The first and second underlayers

506 and 505 can affect the propagation of light by introducing an additional refractive index boundary. The first and second underlayers 506 and 505 also help in bonding the grating structures 501 to the substrate 507, ensuring structural integrity.

[0050] In some configurations, the first and second underlayer 506 and 505 comprise a stack of thin film materials with different refractive indices. In some other configurations, there is only one layer thin film material with one refractive index. The underlayer material is chosen for its optical compatibility with the grating material(s) (i.e., the first grating material 501a and the second grating material 501b) and the substrate 507. The underlayer material may have a refractive index that is intermediate between the grating material(s) and the substrate 507, to minimize reflection losses at the interface. If designed with particular optical properties, the first and second underlayers 506 and 505 can also contribute to the modulation of light as it transitions from the substrate 507 to the grating structures 501, which can further help to suppress parasitic orders or enhance the efficiency of the desired diffraction orders.

[0051] In operation, the depicted asymmetrical grating 500 within the waveguide functions to modulate the phase and direction of light propagation, thereby reducing parasitic diffraction transitions. Light incident on the grating would be diffracted at angles determined by the grating's spatial period (the distance between similar points on adjacent grating structures 501) and the wavelength of the light. The asymmetry in the grating's shape can be designed to preferentially diffract light into certain orders while suppressing others (parasitic orders).

[0052] When light is coupled into the waveguide and interacts with these asymmetric gratings, the variation in grating depth and angle causes a differential phase shift in the light diffracted by different parts of the grating. The gratings are configured such that the desired light paths experience constructive interference, reinforcing the signal in the intended direction. Conversely, the parasitic paths undergo destructive interference, which diminishes their amplitude and mitigates their presence in the signal.

[0053] The first and second encapsulation layers 503 and 504 include refractive indices lower than the first and second grating materials 501a and 501b, serve to create a controlled optical environment. The first and second encapsulation layers

503 and 504 prevent the coupling of light into parasitic modes by providing an index contrast that favors the propagation of the desired diffracted orders while suppressing the undesired ones. The first and second underlayers 506 and 505, situated beneath the grating structures 501, may also contribute to the overall wavefront shaping by providing a foundation that supports the differential phase modulation effected by the grating structures 501.

[0054] Stated differently, in some embodiments, the first encapsulation layer 503 can have any refractive index. The refractive index can be tuned to create a phase shift that reinforces the constructive interference of the desired diffraction order and destructively interferes with the parasitic orders. The second encapsulation layer 504 has a refractive index greater than 1 (which is the RI of air) and less than the effective refractive index of the grating materials. The second encapsulation layer 504 is designed to provide a transition in refractive index to reduce reflections or other parasitic effects at the boundary with the grating structures 501. The first grating material 501a has a refractive index n_g that is less than that of the substrate 507 n_s . The second grating material 501b (if used) has a refractive index different than the refractive index of the first grating material 501a. The refractive index of the underlayer(s) (i.e., the first underlayer 506 and the second underlayer 505) n_u is higher than that of the grating material(s) n_g . Underlayer(s) with a higher RI than that of the grating material can act as a waveguide, which confines the light to the grating region, enhancing the efficiency of the desired order and preventing the light from leaking into unwanted directions.

[0055] FIGS. 6A-6E illustrate different embodiments of an optical device in different configurations that include encapsulated asymmetric gratings. FIGS. 6A – 6D illustrate an optical device in configurations that include double-sided encapsulated low-refractive index (RI) gratings with optional underlayer(s) and AR coatings. FIG. 6E illustrates an optical device in a configuration that includes a single-sided 2D encapsulated low-RI gratings with an optional underlayer and AR coatings.

[0056] FIG. 6A illustrates the optical device (i.e., a waveguide combiner) in a first configuration 600. The first configuration 600 includes a slanted IC 601 with an optional encapsulation 602 a slanted EOC1 603a with an optional encapsulation 604, and a slanted EOC2 603b with the optional encapsulation 604. The slanted IC 601

and the slanted EOC1 603a are formed over a first surface 607a of a substrate 607 (such as substrate 203). The slanted EOC2 603b is formed over a second surface 607b of the substrate 607 that opposes the first surface 607a of the substrate 607.

[0057] In the first configuration 600, the slanted IC 601 includes slanted grating structures 601a, the slanted EOC1 603a includes slanted grating structures 603a-1, and the slanted EOC2 603b includes slanted grating structures 603b-1. The slanted grating structures 601a of the IC 601, the slanted gratings structures 603a-1 of the EOC1 603a, and the slanted gratings structures 603b-1 of the EOC2 603b are in an asymmetric configuration that can tailor the diffracted light's directionality. Asymmetric gratings can be designed to have different period or shape on each side of the grating line, which allows for the preferential direction of certain diffraction orders and the suppression of others, leading to parasitic order mitigation. The slanted grating structures 603a, 603a-1 and 603b-1, are designed with an angle relative to the perpendicular of the substrate 607 surface (i.e., the first surface 607a and/ or the second surface 607b, respectively), which can cause the incident light to diffract more strongly in the direction of the slant than in the direction opposite. The slanted grating structures 603a, 603a-1 and 603b-1 (as opposed to symmetric, like square-wave binary grating structures) can be designed to favor the +1st diffraction order while suppressing the -1st order. This intrinsic property of the grating shape contributes to reducing parasitic orders because the energy is not equally distributed among the multiple diffraction orders.

[0058] In one or more embodiments, the optional encapsulation 602 and the optional encapsulation 604 include the first encapsulation layer 503, the second encapsulation layer 504, or both. As noted above, the optical device may further include one or more underlayers 605 disposed directly onto the first surface 607a and/or the second surface 607b of the substrate 607. In one or more embodiments, the one or more underlayers 605 includes the first underlayer 506 and/or the second underlayer 505, or any other suitable quantity of underlayers. In one or more examples, the optical device further includes an optional AR coating 606. The optional AR coating 606 may have the same or different RI than the one or more underlayers 605. As shown in FIG. 6A (and FIGS. 6B-6E), the optional AR coating 606 may cover portions of the one or more underlayers 605 that do not include a grating (such as an IC or an EOC) formed thereon. For example, as illustrated in FIG. 6A (and FIGS. 6B-

6E), the optional AR coating 606 is disposed between the slanted IC 601a and the slanted EOC1 603a.

[0059] In other embodiments, the optional AR coating 606 may cover each of the exposed portions of the underlayer 605. Stated differently, the optional AR coating 606 may be disposed on the portions of the underlayer 605 on the first surface 607a that are positioned between the slanted IC 601 and the slanted EOC1 603a and portions of the underlayer 605 on the first surface 607a that are exposed between the slanted grating structures 601a and the slanted grating structures 603a-1. The optional AR coating 606 may also be disposed on the each of the exposed portions of the underlayer 605 on the second surface 607b including the portions of the one or more underlayers 605 disposed between the slanted grating structures 603b-1. Furthermore, in embodiments where the optional AR coating 606 covers each exposed portion of the underlayer 605, the optional encapsulations 602 and 604 are each disposed over the optional AR coating 606 disposed between the grating structures.

[0060] Furthermore, in one or more embodiments, the optional AR coating may not be used and the optional encapsulations 602 and 604 cover each exposed portion of the one or more underlayers 605. Here, the optional encapsulations 602 and 604 are deposited with a greater thickness over the gratings. For example, the thickness of the optional encapsulations 602 and 604 deposited over the portions of the one or more underlayers 605 positioned between of the slanted IC 601a and the slanted grating structure would have a lower thickness than the optional encapsulations 602 and 604 disposed over the slanted IC 601 and the slanted EOC1 603a.

[0061] FIG. 6B illustrates the optical device in a second configuration 610. The second configuration includes a blazed IC 611 with the optional encapsulation 602, a blazed EOC1 613a with the optional encapsulation 604 and a blazed EOC2 613b with the optional encapsulation 604. The blazed IC 611 and the blazed EOC1 613a are formed over a first surface 607a of the substrate 607. The blazed EOC2 603b is formed over the second surface 607b of the substrate 607.

[0062] In the second configuration, the blazed IC 611 includes blazed grating structures 611a, the blazed EOC1 613a includes blazed grating structures 613a-1, the blazed EOC2 613b includes blazed grating structures 613b-1. In one or more

embodiments, the blazed grating structures 611a, 613a-1, and 613b-have a sawtooth-like pattern, where each facet is angled to preferentially direct light into a certain diffraction order. The blazed IC 611 will thus have a high coupling efficiency for directing the incoming light into the waveguide at the desired angle, increasing the efficiency of the light coupling into a specific mode of the waveguide. Similarly, the blazed EOC1 613a and the blazed EOC2 613b are designed with a blazed grating profile. The blazed grating structures 613a-1 and 613b-1 are shaped for expanding and extracting the guided light out of the optical device (e.g., waveguide) in a controlled manner. The combination of the blazed IC 611, the blazed EOC1 613a, and the blazed EOC2 613b ensures that the optical device in the second configuration 610 can couple light in and out with high efficiency and very specific directionality. The blazed grating structures 611a, 613a-1, and 613b-1 of the blazed IC 611, the blazed EOC1 613a, and the blazed EOC2 613b, respectively, can inherently reduce the intensity of unwanted diffraction orders, as the geometry is optimized to enhance a specific order at the expense of others.

[0063] FIG. 6C illustrates the optical device in a third configuration 620. In the third configuration 620, the optical device includes a binary IC 621 with the optional encapsulation 602 along with the slanted EOC1 603a with the optional encapsulation 604, and the slanted EOC2 603b with the optional encapsulation 604. The binary IC 621 includes binary grating structures 621a. The binary grating structures 621a are periodic grating structures with two levels of etching, often resembling a square-wave pattern. The binary grating structures 621a are designed to diffract incident light into specific diffraction orders with high efficiency. The binary nature of the binary grating structures 621a allows for easier fabrication as compared to blazed gratings and can be designed to work well at certain wavelengths or for certain polarization states. As noted above, the slanted grating structures 603a-1 and 603b-1, are designed with an angle relative to the perpendicular of the substrate 607 surface (i.e., the first surface 607a or the second surface 607b, respectively), which can cause the diffracted light to exit at a non-normal angle. The slanted grating structures 603a-1 and 603b-1 can be used to spread out the light in a particular direction and are often used for out-coupling light in a controlled angular distribution.

[0064] FIG. 6D illustrates an optical device in a fourth configuration 630. The fourth configuration 630 includes the binary IC 621 with the optional encapsulation 602, the

blazed EOC1 613a with the optional encapsulation 604, and the blazed EOC2 613b with the optional encapsulation 604. Advantageously, by combining the binary IC 621 with both the blazed EOC1 613a and the blazed EOC2 613b could allow for complex manipulation of light, taking advantage of the binary IC 621 (i.e., the binary grating structures 621a) properties and the efficiency of the blazed EOC1 613a and the blazed EOC2 613b (i.e., the blazed grating structures 613a-1 and 613b-1).

[0065] FIG. 6E illustrates an optical device in a fifth configuration 640. The fifth configuration 640, includes the binary IC 621. Furthermore, the fifth configuration 640 includes the slanted EOC1 603a and the slanted EOC2 603b, which are both formed on the first surface 607a of the substrate 607. Each of the EOCs (the slanted EOC1 603a, the slanted EOC2 603b, or any other combination of EOCs) on the first surface 607a can include either slanted or blazed grating structures. For example, the fifth configuration can include the slanted EOC1 603a and the blazed EOC2 613b, the blazed EOC1 613a and the slanted EOC1 603b, the blazed EOC1 613a and the blazed EOC2, or any other combination thereof. In one or more embodiments, the slanted EOC1 603a and the slanted EOC2 603b (or any other suitable combination of EOCs formed on the first side of the substrate 607) are designed such that their grating structures (e.g., slanted grating structures 603a-1 and 603b-1) intersect or interact across two spatial dimensions. Thus forming a 2-D overlap region 643 between the slanted EOC1 603a and the slanted EOC2 603b (or any other combination of EOCs). As light encounters each grating, the light will be diffracted according to the grating's orientation and periodicity. If each EOC has a different orientation (e.g., one is horizontal and the other is vertical), the grating structures (e.g., the slanted grating structures 603a-1 and 603b-1, the blazed grating structures 611a, and 613a, and the like) will diffract light in their respective directions. The 2-D overlap region 643 is where the influence of both the slanted EOC1 603a and the slanted EOC2 603b (or any other combination of EOCs) on the light paths coexists. In the 2-D overlap region 644, the diffraction effects of both the slanted EOC1 603a and the slanted EOC2 603b are superimposed. This means that light can be manipulated in two orthogonal planes, allowing for more sophisticated control over the directionality and phase of the diffracted light. Depending on the phase relationship between the light diffracted by each EOC in the 2-D overlap region 243, there may be constructive

or destructive interference, which can be used to tailor the intensity pattern of the light exiting the EOCs.

[0066] The 2-D overlap region 643 helps mitigate parasitic orders by employing two mechanisms: spatial filtering and diffractive mode management. By having the 2-D overlap region 643, the EOCs can be arranged such that the desired diffraction orders are reinforced in specific directions, while the undesired parasitic orders are suppressed. The overlap region acts as a spatial filter, allowing only certain directions of light propagation that are consistent with the function of both EOCs. This can be especially effective if the EOCs are designed to have diffraction efficiencies that vary across the aperture, further suppressing unwanted orders. The overlapping EOCs can be designed such that they diffract light into specific modes that constructively interfere to enhance the main lobe (the desired output), while the modes that would lead to parasitic orders destructively interfere with each other. By carefully controlling the phase and amplitude of the light diffracted by each EOC, parasitic orders can be canceled or reduced.

[0067] As noted above, the grating structures (e.g., the slanted grating structures 601a, 603a-1, and 603b-1, the blazed grating structures 611a, and 613a, and the like) may include one or more grating materials (such as the first grating material 501a the second grating material 501b). The encapsulated grating structures leverage an asymmetric grating profile along with strategic RI configurations to control the phase and amplitude of the diffracted light. By doing so, the grating structures enhance the desired diffraction order's efficiency while suppressing parasitic orders, leading to higher performance optical devices. In some embodiments, the first encapsulation layer 503 can have any refractive index. The refractive index can be tuned to create a phase shift that reinforces the constructive interference of the desired diffraction order and destructively interferes with the parasitic orders. AR coatings are used to minimize the reflection at the surface of the grating, which can improve efficiency by allowing more light to enter or exit the grating without being reflected away.

[0068] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. An optical device, comprising:
 - a substrate;
 - an input coupler disposed on a first surface of the substrate and configured to receive input light;
 - a first output coupler disposed on the first surface of the substrate; and
 - a second output coupler disposed on a second surface of the substrate,wherein the first output coupler and the second output coupler comprise asymmetric grating structures the first surface of the substrate opposes the second surface of the substrate.
2. The optical device of claim 1, wherein the asymmetric grating structures have asymmetrical geometric shapes, asymmetrical periodicities along different directions, or asymmetrical material compositions.
3. The optical device of claim 1, further comprising an encapsulation layer encapsulating at least one of the first output coupler or the second output coupler.
4. The optical device of claim 3, further comprising an underlayer disposed between the encapsulation layer and the substrate.
5. The optical device of claim 1, wherein the input coupler comprises at least one of a slanted grating, a blazed grating, or a binary grating.
6. The optical device of claim 1, wherein the first output coupler and the second output coupler comprise at least one of a slanted grating or a blazed grating.
7. An optical device, comprising:
 - a substrate;
 - at least one underlayer disposed on the substrate, the at least one underlayer having a first refractive index (RI);
 - grating structures disposed on the at least one underlayer, the grating structures comprising a first grating material having a second RI; and

one or more encapsulation layers disposed on portions at least one underlayer positioned between the grating structures and over the grating structures, wherein a first encapsulation layer of the one or more encapsulation layers has a third RI, wherein the third RI is less than the second RI, and wherein the second RI is less than the first RI.

8. The optical device of claim 7, wherein the grating structures include an asymmetric profile comprising at least one of a slanted profile or a blazed profile.

9. The optical device of claim 7, wherein the grating structures are configured to induce destructive interference for parasitic diffraction orders and induce constructive interference for non-parasitic diffraction orders.

10. The optical device of claim 7, further comprising an anti-reflective (AR) coating disposed over exposed portions of the at least one underlayer.

11. The optical device of claim 7, wherein the substrate has a fifth RI that is less than the first RI.

12. An optical device, comprising:
a substrate;
an input coupler;
a first output coupler comprising a first grating structure having a first directional periodicity along a first axis; and
a second output coupler comprising a second grating structure having a second directional periodicity along a second axis different from the first axis,
wherein the input coupler, the first output coupler, and the second output coupler are disposed on a single side of the substrate, and
wherein the first grating structure and the second grating structure overlap in a defined region on the substrate to form a two-dimensional (2-D) overlap region.

13. The optical device of claim 12, wherein the 2-D overlap region is configured as a spatial filter allowing light propagation along certain directions.

14. The optical waveguide of claim 12, wherein the 2-D overlap region is configured to suppress parasitic diffraction orders and enhance non-parasitic diffraction orders.
15. The optical waveguide of claim 12, wherein the first grating structure and the second grating structure comprise a plurality of asymmetric waveguide gratings, each asymmetric waveguide grating being configured to provide constructive diffractions or destructive diffractions along a respective axis of periodicity.
16. The optical waveguide of claim 12, wherein each of the first grating structure and the second grating structure is encapsulated by one or more encapsulation layers, wherein refractive indices of the one or more encapsulation layers are lower than refractive indices of the first grating structure and the second grating structure.
17. A method comprising:
 providing a double-sided grating structure having an input coupler (IC) and two expanding output couplers (EOCs);
 directing an input light through the IC, where the IC diffracts the input light into a first k-space distribution;
 expanding the first k-space distribution through the two EOCs to form a second, larger k-space distribution;
 reducing parasitic order transitions via one or more asymmetric grating structures included in at least one of the two EOCs; and
 outputting, via at least one of the two EOCs, a wavefront having a field of view (FoV).
18. The method of claim 17 wherein the two EOCs selectively expand different color components of the input light to provide uniform outcoupled color illumination across the FoV.
19. The method of claim 17, further comprising aligning grating vectors for a red color component to overlap within a red FoV, aligning grating vectors for a green color component to overlap within a green FoV, and aligning grating vectors for a blue color component to overlap within a blue FoV.

20. The method of claim 17, wherein the asymmetric grating structures have asymmetrical geometric shapes, asymmetrical periodicities along different directions, or asymmetrical material compositions.