HIGH-CONTRAST WAVEGUIDES WITH ENGINEERED SURFACES

BACKGROUND

Field

[0001] Embodiments of the present disclosure generally relate to waveguide combiners. More specifically, embodiments described herein provide for waveguide combiners having roughened portions.

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 three-dimensionally generated and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

[0003] Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhance or augment the environment that the user experiences. Image sharpness of the virtual image may be affected by the environment.

[0004] One challenge is displaying a virtual image overlaid on an ambient environment. Waveguide combiners, such as augmented reality waveguide combiners, are used to assist in overlaying images. Generated light is propagated through a waveguide combiner until the light exits the waveguide combiner and is overlaid on the ambient environment. To do so, the generated light needs to undergo total internal reflection (TIR). Backscattering also occurs, which interferes with TIR within the waveguide combiner. Optical devices may require coating the edge of the waveguide combiner with a light-absorbent layer to reduce backscattering. However, the light-absorbent layer increases manufacturing and design complexity and may reduce the aesthetic of the HMD.

[0005] Accordingly, there is a need for improvements to augmented reality technology.

SUMMARY

[0006] Embodiments described herein generally relate to waveguide combiners for augmented reality. More particularly, the present disclosure relates to systems and methods for waveguide combiners having roughened portions.

[0007] In an embodiment, a waveguide is provided. The waveguide includes a substrate having an edge, an input coupling grating having a first plurality of structures and an output coupling grating having a second plurality of structures disposed over the substrate. The waveguide also includes at least one roughened segment formed into the substrate along the edge between the edge and at least one of the input coupling grating and the output coupling grating, the at least one roughened segment having roughening elements disposed in the substrate.

[0008] In another embodiment, a waveguide is provided. The waveguide includes a substrate having an edge, a top surface, a bottom surface opposing the top surface, an input coupling grating having a first plurality of structures and an output coupling grating having a second plurality of structures disposed over the top surface of the substrate. The waveguide also includes a first roughened segment formed into the top surface of the substrate along the edge between the edge and at least one of the input coupling grating and the output coupling grating over the top surface. The first roughened segment has roughening elements disposed in the top surface of the substrate. The waveguide also includes a second roughened segment formed into the bottom surface of the substrate along the edge, the second roughened segment having roughening elements disposed in the bottom surface of the substrate

[0009] In yet another embodiment, a waveguide is provided. The waveguide includes a substrate having an edge, a top surface, a bottom surface opposing the top surface, an input coupling grating having a first plurality of structures and an output coupling grating having a second plurality of structures disposed over the top surface of the substrate. The waveguide also includes a first continuous roughened segment formed into the top surface of the substrate along an entirety of the edge between the edge and at least one of the input coupling grating and the output coupling grating.

The first continuous roughened segment has roughening elements disposed in the top surface of the substrate

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] 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 of the present disclosure and are therefore not to be considered limiting of its scope, and the present disclosure may admit to other equally effective embodiments.

[0011] Figure 1 illustrates a front view of a waveguide, according to certain embodiments.

[0012] Figures 2A, 2B, and 2C illustrate a cross-sectional, side view of a portion of the waveguide of Figure 1, according to certain embodiments.

[0013] Figures 3A, 3B, and 3C illustrate a cross-sectional, side view of a portion of a waveguide, according to certain embodiments.

[0014] Figures 4A, 4B, and 4C illustrate a cross-sectional, side view of a portion of a waveguide, according to certain embodiments.

[0015] Figure 5A illustrates a front view of a waveguide, according to certain embodiments.

[0016] Figures 5B, 5C, and 5D illustrate a cross-sectional, side view of a portion of the waveguide of Figure 5A, according to certain embodiments.

[0017] Figure 6A illustrates a front view of a waveguide, according to certain embodiments.

[0018] Figure 6B illustrates a cross-sectional, side view of a portion of the waveguide of Figure 6A, according to certain embodiments.

[0019] 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

[0020] Embodiments herein are generally directed to waveguide combiners for augmented reality. More particularly, the present disclosure relates to systems and methods for waveguide combiners having roughened portions.

[0021] The relationship between backscattering and total internal reflection (TIR) within a waveguide combiner provides challenges affecting the overall performance of an augmented reality (AR) display. TIR is observed when light traveling within the waveguide material strikes the boundary with a different material having a different refractive index at an angle exceeding a critical angle. At this critical angle, the light is completely reflected back into the waveguide instead of refracting out, e.g., out-scattering, and escaping. TIR ensures efficient light guidance through the waveguide with minimal losses, resulting in a bright and clear AR image. Backscattering, however, refers to an unwanted phenomenon where light reflects within the waveguide material instead of undergoing TIR and propagating towards the eye of a user. This scattering effect reduces the efficiency of light transmission, leading to several performance deficiencies such as decreased brightness, blurred images, and uneven illumination. The intended path of light rays undergoing TIR within the waveguide is disrupted by backscattering, causing the light to bounce around and lose energy with each interaction, thereby diminishing the overall efficiency of TIR and potentially distorting the AR image. Moreover, backscattering scatters light in various directions, including back towards the light source, which can interfere with the original light rays undergoing TIR and cause unwanted secondary reflections and ghosting effects within the AR image.

[0022] To address backscattering, the edge of an outer surface of a waveguide combiner is traditionally blackened. The blackened edge acts as an absorbing layer, absorbing light that contacts the outer surface thereby preventing light from backscattering inside the waveguide.

[0023] While a blackened edge improves the performance of a waveguide combiner, it presents challenges. The blackened edge effectively blocks light from

reaching the eye of the user in those areas, reducing the overall usable field of view (FOV). The extent of which depends on the thickness and design of the blackened edge. Achieving a uniformly blackened and smooth edge on the waveguide can add complexity to the manufacturing process, and any imperfections or inconsistencies in the blackening process could lead to uneven light absorption, affecting the visual quality of the AR image. Additionally, the blackened edge may reduce the aesthetic of the waveguide, especially if the blackened edge is thick or prominent.

[0024] The present disclosure provides a solution to backscattering in a waveguide without blackening the edge of the waveguide. In particular, the present disclosure provides for a waveguide having at least one roughened segment formed into the substrate of the waveguide along a desired edge of the substrate. A segment is "roughened" by being patterned or etched into roughening elements having various shapes, such as rectangular or binary shapes, blazed shapes, or triangular shapes. The at least one roughened segment may be formed into the top or outward-facing surface of the substrate, the bottom or user-facing surface of the substrate, or a combination of both.

[0025] Figure 1 is a front view of a waveguide 100. It is to be understood that the waveguide 100 described herein is an exemplary waveguide and that other waveguides may be used with or modified to accomplish aspects of the present disclosure. The waveguide 100 includes a plurality of structures 102. The structures 102 may be disposed over, under, or on a surface 103 of a substrate 101, or disposed in the substrate 101. The structures 102 are nanostructures have a sub-micron critical dimension, e.g., a width less than 1 micrometer. Regions of the structures 102 correspond to one or more gratings 104. In one embodiment, which can be combined with other embodiments described herein, the waveguide 100 includes at least a first grating 104a corresponding to an input coupling grating and a third grating 104c corresponding to an output coupling grating. In another embodiment, which can be combined with other embodiments described herein, the waveguide 100 further includes a second grating 104b. The second grating 104b corresponds to a pupil expansion grating or a fold grating.

[0026] The waveguide 100 also includes an edge 106 that is along a periphery of the substrate 101. The substrate 101 includes at least one roughened segment 110

on the edge 106 of the substrate 101. The at least one roughened segment 110 is formed into the substrate 101. The substrate 101 is patterned, including the at least one roughened segment 110, before dicing into individual parts. The at least one roughened segment 110 extends from the edge 106 of the substrate 101 inward for a roughening distance 108. The roughening distance 108 may be uniform across the at least one roughened segment 110, may also vary, e.g., increase or decrease, along the edge 106 of the substrate 101. For example, the roughening distance 108 of the at least one roughened segment 110 may increase along the edge 106 in a step-wise fashion, a linear fashion, or parabolic fashion.

[0027] The at least one roughened segment 110 is a patterned or etched segment of the substrate 101 that includes the formation of roughening elements, discussed in reference to Figures 2A-4C, of various shapes, particularly rectangular and triangular shapes. The roughening elements of the at least one roughened segment 110 allow the roughened segment to have a surface roughness of about 0.1 μm to about 5 μm, such as about 1 μm to about 3 μm. The increased surface roughness improves out-scattering of light within the waveguide that would otherwise backscatter, thereby improving contrast and brightness levels.

[0028] When light interacts with triangular or rectangular shapes, the resulting scattering effect is influenced by several factors. If the size of the triangular or rectangular shapes is comparable to the wavelength of the light, the scattering process is dominated by diffraction, where light bends around the edges of the structures, causing the light to out-scatter in different directions. If the structures are smaller than the wavelength, the roughening elements act as point scatterers, causing the light to scatter in various directions based on the specific geometry of the roughening elements. The angle at which light hits the roughening elements significantly impacts the scattering pattern, with different angles leading to varying intensities of light scattered in different directions. The material properties of the roughening elements, such as their refractive index and surface roughness, influence how light interacts with the structures, with a higher refractive index generally leading to more significant bending of light, while rough surfaces can cause additional scattering due to surface unevenness. Despite the complexity of the overall scattering pattern, the roughening elements provide better incident angles that promote out-scattering of light within the waveguide that will not undergo TIR. This provides

improved contrast and overall performance of the waveguide without needing to add additional blackening material to the surface of the substrate.

[0029] Figures 2A-2C illustrate a cross-sectional, side view of a portion of the waveguide 100 of Figure 1, according to certain embodiments. Figure 2A illustrates a substrate portion 200A of the waveguide 100. A roughened segment 110A is formed into the substrate 101 extending from the edge 106 inward. The roughened segment 110A includes a plurality of roughening elements 202A and a plurality of trenches 204 between each of the plurality of roughening elements 202A. In this embodiment, the plurality of roughening elements 202A are binary where each of the plurality of roughening elements 202A have sidewalls that are substantially perpendicular to a top surface 112 of the substrate. Each of the roughening elements 202A includes an element width 206A and each of the trenches 204 includes a trench width 208. The plurality of roughening elements 202A each includes an element depth 210A that extends from an outer surface of the substrate 101. The plurality of roughening elements 202A provide a roughness to the roughened segment 110A of about 0.1 μm to about 5 μm, such as about 1 μm to about 3 μm.

[0030] Similarly, Figure 2B illustrates a substrate portion 200B of the waveguide 100. A roughened segment 110B is formed into the substrate 101 extending from the edge 106 inward. The roughened segment 110B includes a plurality of roughening elements 202B at an element depth 210B. Each of the plurality of roughening elements 202B includes an element width 206B that may be uniform throughout the roughened segment 110B. Alternatively, the element width 206B may vary throughout the roughened segment 110B in a pattern (not shown) to achieve the desired backscattering prevention. In this embodiment, the roughened segment 110B is blazed. Each of the plurality of roughening elements 202B also includes a blazed side 212 at a blazing angle 214 from an element axis 220 that is perpendicular to the surface of the substrate 101. The blazing angle 214 may be 90 degrees or less, such as about 5 degrees to about 85 degrees, such as about 20 degrees to about 60 degrees, such as about 45 degrees. The plurality of roughening elements 202B provide a roughness to the roughened segment 110B of about 0.1 μm to about 5 μm, such as about 1 μm to about 3 μm.

[0031] Figure 2C illustrates a substrate portion 200C of the waveguide 100. A roughened segment 110C is formed into the substrate 101 extending from the edge 106 inward. The roughened segment 110C includes a plurality of roughening elements 202C at an element depth 210C. The plurality of roughening elements 202C includes a. element width 206C that may be uniform throughout the roughened segment 110C. Alternatively, the element width 206C may vary throughout the roughened segment 110C in a pattern (not shown) to achieve the desired backscattering prevention. In this embodiment, the roughened segment 110C is triangular. Each of the plurality of roughening elements 202C also includes a first slanted side 216A and a second slanted side 216B. The first slanted side 216A includes a first slanting angle 218A from an element axis 220 that is perpendicular to the surface of the substrate 101. Similarly, the second slanted side 216B includes a second slanting angle 218B from the element axis 220 and adjacent to the first slanting angle 218A on an opposing side of the element axis 220. Each of the first slanting angle 218A and the second slanting angle 218B may be 90 degrees or less, such as about 5 degrees to about 85 degrees, such as about 20 degrees to about 60 degrees, such as about 45 degrees. The first slanting angle 218A and the second slanting angle 218B may be equal. Alternatively, the first slanting angle 218A and the second slanting angle 218B may differ, e.g., the first slanting angle 218A is greater than the second slanting angle 218B or the first slanting angle 218A is less than the second slanting angle 218B. Additionally, the first slanting angle 218A and the second slanting angle 218B may be non-uniform across the roughened segment 110C as desired. For example, the first slanting angle 218A and the second slanting angle 218B may be substantially equal adjacent to the edge 106 while the first slanting angle 218A is greater or less than the second slanting angle 218B at the opposing end of the roughened segment 110C. The plurality of roughening elements 202B provide a roughness to the roughened segment 110C of about 0.1 μm to about 5 μm, such as about 1 μm to about 3 μm.

[0032] Figures 3A-3C illustrate a cross-sectional, side view of a portion of the waveguide 100, according to certain embodiments. Figure 3A illustrates a substrate portion 300A of a substrate 101. The substrate portion 300A includes a first roughened segment 310A extending inward from the edge 106 along a top surface 112 of the substrate 101 and a second roughened segment 310B extending inward

from the edge 106 along a bottom surface 114 of the substrate 101. The first roughened segment 310A includes a first plurality of roughening elements 302A and a first plurality of trenches 304A. The first plurality of roughening elements 302A includes a first element width 306A and a first element height 308A. The first element height 308A of the first plurality of roughening elements 302A is a first element depth 312A from a substrate centerline 116. The second roughened segment 310B includes a second plurality of roughening elements 302B and a second plurality of trenches 304B. The second plurality of roughening elements 302B includes a second element width 306B and a second element height 308B. The second element height 308B of the second plurality of roughening elements 302B is a second element depth 312B from a substrate centerline 116. The first roughened segment 310A and the second roughened segment 310B may be uniform. Alternatively, the first roughened segment 310A and the second roughened segment 310B may differ. For example, the first element width 306A may differ from the second element width 306B, e.g., the first element width 306A is bigger than the second element width 306B or the first element width 306A is uniform across the first roughened segment 310A and the second element width 306B varies across the second roughened segment 310B. Further the first element depth 312A and the second element depth 312B may differ, e.g., the first element depth 312A is larger than the second element depth 312B such that the first plurality of roughening elements 302A is etched deeper into the substrate 101 than the second plurality of roughening elements 302B.

[0033] Additionally, the first roughened segment 310A and second roughened segment 310B may extend inwardly from the edge 106 a first roughing distance 314A and a second roughing distance 314B, respectively. The first roughing distance 314A and the second roughing distance 314B may be equal or may differ. For example, the first roughing distance 314A may be greater than the second roughing distance 314B (not shown). The first roughing distance 314A and the second roughing distance 314B may differ depending on the configuration of the first plurality of roughening elements 302A and the second plurality of roughening elements 302B of the first roughened segment 310A and the second roughened segment 310B. For example, the configuration of the first roughened segment 310A in combination with the second roughened segment 310B may require first roughing distance 314A to be

greater than the second roughing distance 314B to reduce backscattering within the substrate 101 to desirable levels.

[0034] Figure 3B shows a substrate portion 300B of a substrate 101. The substrate portion 300B includes a first roughened segment 320A on a top surface 112 of a substrate 101 and a second roughened segment 320B on a bottom surface 114 of the substrate 101. The first roughened segment 320A includes a first plurality of roughening elements 322A having a first blazed side 324A. The first plurality of roughening elements 322A may be angled similar to the plurality of roughening elements 202B of Figure 2B, discussed above. The first plurality of roughening elements 322A includes a first element width 326A and a first element height 328A. The first plurality of roughening elements 322A has a first element depth 330A from the substrate centerline 116. The second roughened segment 320B includes a second plurality of roughening elements 322B having a second blazed side 324B, a second element width 326B, and a second element height 328B. The second plurality of roughening elements 322B has a second element depth 330B from the substrate centerline 116.

[0035] Additionally, the first roughened segment 320A and second roughened segment 320B may extend inwardly from the edge 106 a first roughening distance 332A and a second roughening distance 332B, respectively. The first roughening distance 332A and the second roughening distance 332B may be equal or may differ. For example, the first roughening distance 332A may be greater than the second roughening distance 332B (not shown). The first roughening distance 332A and the second roughening distance 332B may differ depending on the configuration of the first plurality of roughening elements 322A and the second plurality of roughening elements 322B of the first roughened segment 320A and the second roughened segment 320B. For example, the configuration of the first roughened segment 320A in combination with the second roughened segment 320B may require first roughening distance 332A to be greater than the second roughening distance 332B to reduce backscattering within the substrate 101 to desirable levels.

[0036] Figure 3C shows a substrate portion 300C of a substrate 101. The substrate portion 300C includes a first roughened segment 340A on the top surface 112 of the substrate 101 and a second roughened segment 340B on the bottom

surface 114 of the substrate 101. The first roughened segment 340A includes a first plurality of roughening elements 342A. The first plurality of roughening elements 342A includes a first top slanted side 344A and a second top slanted side 346A. The first top slanted side 344A includes a first top slanting angle 348A from an element axis 352 perpendicular to the substrate centerline 116. Similarly, the second top slanted side 346A includes a second top slanting angle 350A from the element axis 352 and adjacent to the first top slanting angle 348A on an opposing side of the element axis 352. Each of the first top slanting angle 348A and the second top slanting angle 350A may be 90 degrees or less, such as about 5 degrees to about 85 degrees, such as about 20 degrees to about 60 degrees, such as about 45 degrees. The first top slanting angle 348A and the second top slanting angle 350A may be equal, e.g., each of the first plurality of roughening elements 342A form an equilateral triangular shape. Alternatively, the first top slanting angle 348A and the second top slanting angle 350A may differ, e.g., the first top slanting angle 348A is greater than the second top slanting angle 350A or the first top slanting angle 348A is less than the second top slanting angle 350A. Additionally, the first top slanting angle 348A and the second top slanting angle 350A may be non-uniform across the first roughened segment 340A as desired. For example, the first top slanting angle 348A and the second top slanting angle 350A may be substantially equal adjacent to the edge 106 while the first top slanting angle 348A is greater or less than the second top slanting angle 350A at the opposing end of the first roughened segment 340A. The first blazed side 324A includes a first element depth 354A from the substrate centerline 116. The first element depth 354A may be uniform or may vary across the first roughened segment 340A (not shown).

[0037] Similarly, the second roughened segment 340B includes a first plurality of roughening elements 342A. The first plurality of roughening elements 342A includes a first bottom slanted side 344B and a second bottom slanted side 346B. The first bottom slanted side 344B includes a first bottom slanting angle 348B from an element axis 352 perpendicular to the substrate centerline 116. Similarly, the second bottom slanted side 346B includes a second bottom slanting angle 350B from the element axis 352 and adjacent to the first bottom slanting angle 348B on an opposing side of the element axis 352. Each of the first bottom slanting angle 348B and the second bottom slanting angle 350B may be 90 degrees or less, such as about 5 degrees to

about 85 degrees, such as about 20 degrees to about 60 degrees, such as about 45 degrees. The first bottom slanting angle 348B and the second bottom slanting angle 350B may be equal. Alternatively, the first bottom slanting angle 348B and the second bottom slanting angle 350B may differ, e.g., the first bottom slanting angle 348B is greater than the second bottom slanting angle 350B or the first bottom slanting angle 348B is less than the second bottom slanting angle 350B. Additionally, the first bottom slanting angle 348B and the second bottom slanting angle 350B may be non-uniform across the second roughened segment 340B as desired. For example, the first bottom slanting angle 348B and the second bottom slanting angle 350B may be substantially equal for roughening elements near the edge 106 while the first bottom slanting angle 348B is greater or less than the second bottom slanting angle 350B for roughening elements at the opposing end of the second roughened segment 340B, e.g., furthest away from the edge 106. The first blazed side 324B includes a first element depth 354B from the substrate centerline 116. The first element depth 354B may be uniform or may vary across the second roughened segment 340B (not shown).

[0038] Additionally, the first roughened segment 340A and second roughened segment 340B may extend inwardly from the edge 106 a first roughening distance 356A and a second roughening distance 356B, respectively. The first roughening distance 356A and the second roughening distance 356B may be equal or may differ. For example, the first roughening distance 356A may be greater than the second roughening distance 356B (not shown). The first roughening distance 356A and the second roughening distance 356B may differ depending on the configuration of the first plurality of roughening elements 342A and the second plurality of roughening elements 342B of the second roughened segment 340B and the second roughened segment 340B. For example, the configuration of the second roughened segment 340B in combination with the second roughened segment 340B may require first roughening distance 356A to be greater than the second roughening distance 356B to reduce backscattering within the substrate 101 to desirable levels.

[0039] Figures 4A-4C illustrate a cross-sectional, side view of a portion of the waveguide 100, according to certain embodiments. Each of Figures 4A-4C illustrates exemplary combinations of roughened portion configurations. Although these

exemplary combinations are discussed, any combination of roughened portion configurations on a top and bottom surface of the substrate are contemplated.

[0040] For example, Figure 4A shows a substrate portion 400A of the substrate 101. The substrate portion 400A includes a first roughened segment 410A having a first plurality of roughening elements 412A formed in the top surface 112 of the substrate 101 extending inward from the edge 106 of the substrate 101. The substrate portion 400A also includes a second roughened segment 410B having a second plurality of roughening elements 412B formed in the bottom surface 114 of the substrate 101 extending inward from the edge 106. The first roughened segment 410A and the second roughened segment 410B may differ, e.g., the first plurality of roughening elements 412A and the second plurality of roughening elements 412B differ. In this embodiment, the first roughened segment 410A may be binary such that the first plurality of roughening elements 412A are configured similarly to the plurality of roughening elements 202A of Figure 2A. The second roughened segment 410B may be angled such that the second plurality of roughening elements 412B are configured similarly to the plurality of roughening elements 202B of Figure 2B.

[0041] Figure 4B shows a substrate portion 400B of the substrate 101 that includes a first roughened segment 420A having a first plurality of roughening elements 422A formed in the top surface 112 of the substrate 101 extending inward from the edge 106 of the substrate 101 and a second roughened segment 420B having a second plurality of roughening elements 422B formed in the bottom surface 114 of the substrate 101 extending inward from the edge 106. As shown, the first roughened segment 420A may be angled such that the first plurality of roughening elements 422A are configured similarly to the plurality of roughening elements 202B of Figure 2B. The second roughened segment 420B may be binary such that the second plurality of roughening elements 422B are configured similarly to the plurality of roughening elements 202A of Figure 2A.

[0042] Figure 4C shows a substrate portion 400C including a 430A having a first plurality of roughening elements 432A formed in the top surface 112 of the substrate 101 extending inward from the edge 106 and a second roughened segment 430B having a second plurality of roughening elements 432B formed in the bottom surface 114 of the substrate 101 extending inward from the edge 106. In this embodiment,

the first roughened segment 430A is triangular such that the first plurality of roughening elements 432A are configured similarly to the plurality of roughening elements 202C of Figure 2C, and the second roughened segment 430B is an angled such that the second plurality of roughening elements 432B are configured similarly to the plurality of roughening elements 202B of Figure 2B.

[0043] Figure 5A illustrates a front view of a waveguide 500, according to certain embodiments. The waveguide 500 includes plurality of roughened segments 510. Each of the plurality of roughened segments 510 may be configured according to embodiments of Figures 2A-4C.

[0044] Figures 5B-5D illustrate a cross-sectional, side view of a portion of the waveguide 500, according to certain embodiments.

[0045] Figure 5B shows a substrate portion 520A having a first roughened segment 522A along a first portion of the edge 106 and a second roughened segment 524A extending inward from the edge 106 along the top surface 112 of the substrate 101. The first roughened segment 522A and the second roughened segment 524A may be configured the same, e.g., both uniform and binary, blazed, or angled. Alternatively, the first roughened segment 522A and the second roughened segment 524A may be configured the differently. As shown in Figure 5B, for example, the first roughened segment 522A is binary, similar to the roughened segment 110A of Figure 2A. The second roughened segment 524A is angled, similar to the roughened segment 110B of Figure 2B. In this embodiment, the bottom surface 114 of the substrate 101 is not roughened, e.g., the bottom surface 114 is substantially planar, though it is contemplated that the bottom surface 114 may include at least one of the plurality of roughened segments 510.

[0046] Figure 5C shows a substrate portion 520B having a first roughened segment 522B and a second roughened segment 524B extending inward from the edge 106 along the top surface 112 of the substrate 101. As discussed above, the first roughened segment 522B and the second roughened segment 524B may differ. In this embodiment, the first roughened segment 522B is angled, similar to the roughened segment 110B of Figure 2B. The second roughened segment 524B is triangular, similar to the roughened segment 110C of Figure 2C. In this embodiment, the bottom surface 114 of the substrate 101 is not roughened, e.g., the bottom surface

114 is substantially planar, though it is contemplated that the bottom surface 114 may include the plurality of roughened segments 510.

[0047] Figure 5D shows a substrate portion 520C having a first roughened segment 522C extending inward from the edge 106 along the top surface 112 of the substrate 101 and a second roughened segment 524C extending inward from the edge 106 along the bottom surface 114 of the substrate 101. As discussed above, the first roughened segment 522C and the second roughened segment 524C may differ. In this embodiment, the first roughened segment 522C is binary, similar to the roughened segment 110A of Figure 2A. The second roughened segment 524C is binary, similar to the roughened segment 110A of Figure 2A.

[0048] Figure 6A illustrates a front view of a waveguide, according to certain embodiments. The waveguide 600 includes a continuous roughened segment 610 formed into a surface, e.g., the top surface 112, of the substrate 101 along an entirety of the edge 106 of the substrate 101, e.g., there are no un-roughened segments along the edge 106 of the substrate. The continuous roughened segment 610 may be configured according to embodiments of Figures 2A-4C. The continuous roughened segment 610 may be uniform throughout the edge 106, e.g., having only one configuration of roughening elements. Alternatively, as shown in Figure 6B, the continuous roughened segment 610 may include a combination of configurations for portions of the continuous roughened segment 610, e.g., combinations of configurations of roughening elements such as binary, blazed, or triangular.

[0049] For example, Figure 6B illustrates a cross-sectional, side view of a substrate portion 620 of the waveguide 600 having a continuous roughened segment 610 with a combination of roughening element configurations, according to certain embodiments. The substrate portion 620 includes the continuous roughened segment 610 having a first roughened portion 630A and a second roughened portion 630B extending inward from the edge 106 along a top surface 112 of the substrate 101. Although, in this embodiment, the bottom surface 114 of the substrate 101 is not roughened, it is contemplated that the bottom surface 114 may also include the continuous roughened segment 610. The first roughened portion 630A may be binary, similar to the roughened segment 110A of Figure 2A, and the second roughened portion 630B may be angled, similar to the roughened segment 110B of Figure 2B.

Although this particular combination is discussed, the first roughened portion 630A and the second roughened portion 630B may be in any configuration discussed in the present disclosure. The continuous roughened segment 610 is continuous, e.g., the first roughened portion 630A and the second roughened portion 630B are directly adjacent such that there is no un-roughened portion between the first roughened portion 630A and the second roughened portion 630B.

[0050] Additionally, the waveguide 600 may include a second continuous roughened segment (not shown) formed into the bottom surface 114 of the substrate 101 along the entirety of the edge 106. Alternatively, the waveguide 600 may have a roughened segment (not shown) formed into the bottom surface along a portion of the edge 106 of the substrate 101 that is not continuous, e.g., there is at least one portion of the edge 106 that is un-roughened or substantially planar. In these embodiments, the second roughened segment or second continuous roughened segment may be configured similarly to the embodiments discussed in the present disclosure.

[0051] The present disclosure provides for a waveguide having at least one roughened segment formed into the substrate of the waveguide along a desired edge of the substrate. A segment is "roughened" by being pattered or etched into roughening elements having various shapes, such as rectangular or binary shapes, blazed shapes, or triangular shapes. The roughening elements provide better incident angles that promote out-scattering of light within the waveguide that will not undergo TIR. This provides improved contrast and overall performance of the waveguide without needing to add additional blackening material to the surface of the substrate.

[0052] When introducing elements of the present disclosure or exemplary aspects or embodiments thereof, the articles "a," "an," "the" and "said" are intended to mean that there are one or more of the elements.

[0053] The terms "comprising," "including" and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0054] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing

from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A waveguide, comprising:

a substrate having an edge;

an input coupling grating having a first plurality of structures and an output coupling grating having a second plurality of structures disposed over the substrate; and

at least one roughened segment formed into the substrate along the edge between the edge and at least one of the input coupling grating and the output coupling grating, the at least one roughened segment having roughening elements disposed in the substrate.

2. The waveguide of claim 1, wherein the at least one roughened segment is binary comprising the roughening elements having sidewalls that are substantially perpendicular to a top surface of the substrate and a plurality of trenches between each of the roughening elements.

3. The waveguide of claim 1, wherein the at least one roughened segment is blazed comprising the roughening elements, each of the roughening elements having a blazed side.

4. The waveguide of claim 1, wherein the at least one roughened segment is triangular comprising the roughening elements, each of the roughening elements having a first slanted side and a second slanted side.

5. The waveguide of claim 1, wherein the at least one roughened segment comprises a first roughened segment having a first plurality of the roughening elements along a first portion of the edge and a second roughened segment having a second plurality of the roughening elements along a second portion of the edge, the first plurality of the roughening elements and the second plurality of the roughening elements being different.

6. The waveguide of claim 1, wherein the at least one roughened segment comprises a roughening distance that varies along the edge of the substrate.

7. A waveguide, comprising:

a substrate having an edge, a top surface, and a bottom surface opposing the top surface;

an input coupling grating having a first plurality of structures and an output coupling grating having a second plurality of structures disposed over the top surface of the substrate;

a first roughened segment formed into the top surface of the substrate along the edge between the edge and at least one of the input coupling grating and the output coupling grating over the top surface, the first roughened segment having roughening elements disposed in the top surface of the substrate; and

a second roughened segment formed into the bottom surface of the substrate along the edge, the second roughened segment having the roughening elements disposed in the bottom surface of the substrate.

8. The waveguide of claim 7, wherein the first roughened segment is binary comprising the roughening elements having sidewalls that are substantially perpendicular to the top surface of the substrate and a plurality of trenches between each of the roughening elements.

9. The waveguide of claim 7, wherein the first roughened segment is blazed comprising the roughening elements, each of the roughening elements having a blazed side.

10. The waveguide of claim 7, wherein the first roughened segment is triangular comprising the roughening elements, each of the roughening elements having a first slanted side and a second slanted side.

11. The waveguide of claim 7, wherein the first roughened segment and the second roughened segment are different.

12. The waveguide of claim 7, wherein the first roughened segment comprises a roughening distance that varies along the edge of the substrate.

13. The waveguide of claim 7, wherein the second roughened segment comprises a roughening distance that differs from a roughening distance of the first roughened segment.

14. A waveguide, comprising:

a substrate having an edge, a top surface, and a bottom surface opposing the top surface;

an input coupling grating having a first plurality of structures and an output coupling grating having a second plurality of structures disposed over the top surface of the substrate; and

a first continuous roughened segment formed into the top surface of the substrate along an entirety of the edge between the edge and at least one of the input coupling grating and the output coupling grating, the first continuous roughened segment having roughening elements disposed in the top surface of the substrate.

15. The waveguide of claim 14, wherein the first continuous roughened segment is binary comprising the roughening elements having sidewalls that are substantially perpendicular to a surface of the substrate and a plurality of trenches between each of the roughening elements.

16. The waveguide of claim 14, wherein the first continuous roughened segment is blazed comprising the roughening elements, each of the roughening elements having a blazed side.

17. The waveguide of claim 14, further comprising a second continuous roughened segment formed into the bottom surface of the substrate along the entirety of the edge.

18. The waveguide of claim 17, wherein the second continuous roughened segment is different from the first continuous roughened segment.

19. The waveguide of claim 14, wherein the first continuous roughened segment comprises a first roughened portion and a second roughened portion that is different from the first roughened portion.

20. The waveguide of claim 14, further comprising a roughened segment formed into the bottom surface of the substrate along a portion of the edge of the substrate.