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DOUBLE-HELIX ONTO A SINGLE LIGHT-GUIDE OPTICAL ELEMENT (LOE)

Abstract

An optical device may include a first waveguide to receive and expand in a first dimension a first portion of guided image beams based on a first image field and provide a first plurality of expanded image beams; a second waveguide to receive and expand in the first dimension one of a second portion of guided image beams and a transmitted second portion of guided image beams corresponding to a second image field that is different from the first image field and to provide a second plurality of expanded image beams, the second waveguide to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams; and a third waveguide to receive and expand in a second dimension the transmitted first plurality of expanded image beams and the second plurality of expanded image beams to provide a third plurality of expanded image beams.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application is based upon and claims the benefit of priority under 35 USC 119(e) of U.S. Patent Application No. 63/417,215 filed on Oct. 18, 2022, and titled “Double-Helix Onto a Single Lightguide Optical Element (LOE),” the disclosure of which is herein incorporated by reference in its entirety.

BACKGROUND

[0002] Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section. The present disclosure relates in general to optical devices and systems related to wearable devices for use in augmented reality applications, more particularly, to an improved wearable device for providing optical information directly to a user.

[0003] Wearable optical devices, such as near eye displays or smart glasses for use in augmented reality applications, are often cumbersome to wear and use, thus limiting their comfort and utility. Current wearable optical devices may also have a limited field-of-view (FoV) which can be undesirable for a user and could affect safety in some situations. However, total internal reflection (TIR) in a light-guide may limit a width of the FoV of the transmitted image. Also, low-refractive index of the light-guide materials may further reduce the available angular range to be transmitted. Finally, increasing the field-of-view may require pushing the limits of geometric boundaries, which can be heavy, expensive and may lead to a product form factor and/or aesthetic appearance which may not be acceptable in the marketplace. What is needed is a solution that addresses these issues, and others.

SUMMARY

[0004] According to an example, an optical device is generally described. The optical device may include a first waveguide configured to receive and expand in a first dimension a first portion of guided image beams based on a first image field and to provide a first plurality of expanded image beams; a second waveguide disposed adjacent to the first waveguide, the second waveguide configured to receive and expand in the first dimension one of a second portion of guided image beams and a transmitted second portion of guided image beams corresponding to a second image field that may be different from the first image field and to provide a second plurality of expanded image beams, the second waveguide configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams; and a third waveguide disposed adjacent to the second waveguide on a side opposite the first waveguide, the third waveguide configured to receive and expand in a second dimension the transmitted first plurality of expanded image beams and the second plurality of expanded image beams to provide a third plurality of expanded image beams.

[0005] According to this example, the optical device wherein the first waveguide may further include a first mirror configured to receive the first portion of guided image beams and provide a reflected first portion of guided image beams; and a first aperture expander positioned in a first region, the first aperture expander may be configured to receive the reflected first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide may be configured to receive the second portion of guided image beams and provide a transmitted

second portion of guided image beams; and wherein the second waveguide may further include a second mirror configured to receive the transmitted second portion of guided image beams and provide a reflected second portion of guided image beams; and a second aperture expander positioned in a second region that may be laterally displaced from the first region, the second aperture expander configured to receive the reflected second portion of guided image beams and provide a second plurality of expanded image beams, wherein the second waveguide may be configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams.

[0006] According to this example, the optical device wherein the first aperture expander may include a first plurality of partially reflecting facets disposed in the first region, the first mirror and the first plurality of partially reflecting facets being parallel to each other and disposed at a first angle relative to a long axis of the first waveguide, and wherein the second aperture expander may further include a second plurality of partially reflecting facets disposed in the second region, the second mirror and the second plurality of partially reflecting facets may be parallel to each other and disposed at a second angle relative to a long axis of the second waveguide, the second angle may be different from the first angle. According to this example, the optical device wherein the reflected first portion of guided image beams may be reflected within the first waveguide by total internal reflection between a first waveguide front surface and a first waveguide rear surface, and wherein the reflected second portion of guided image beams may be reflected within the second waveguide by total internal reflection between a second waveguide front surface and a second waveguide rear surface.

[0007] According to this example, the optical device wherein the first waveguide may further include a first diffraction grating configured to receive the first portion of guided image beams and provide a diffracted first portion of guided image beams; a first aperture expander positioned in a first region, the first aperture expander may be configured to receive the diffracted first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide may be configured to receive the second portion of guided image beams and provide a transmitted second portion of guided image beams; and wherein the second waveguide may further include a third diffraction grating configured to receive the transmitted second portion of guided image beams and provide a diffracted second portion of guided image beams; a second aperture expander positioned in a second region that may be laterally displaced from the first region, the second aperture expander may be configured to receive the diffracted second portion of guided image beams and provide a second plurality of expanded image beams, wherein the second waveguide may be configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams.

[0008] According to this example, the optical device wherein the first aperture expander may include a second diffraction grating configured to receive the diffracted first portion of guided image beams and provide the first plurality of expanded image beams, and wherein the second aperture expander may include a fourth diffraction grating configured to receive the diffracted second portion of guided image beams and provide the second plurality of expanded image beams. According to this example, the optical device wherein the diffracted first portion of guided image beams may be reflected within the first waveguide by total internal reflection between a first waveguide front surface and a first waveguide rear surface, and wherein the diffracted second portion of guided image beams may be reflected within the second waveguide by total internal reflection between a second waveguide front surface and a second waveguide rear surface.

[0009] According to this example, the optical device may further include one of a third stacked waveguide arrangement comprising the first waveguide that may further include a first mirror configured to receive the first portion of guided image beams and provide a reflected first portion of guided image beams; and a first aperture expander may be positioned in a first region, the first aperture expander may include a first plurality of partially reflecting facets disposed in the first

region, the first mirror and the first plurality of partially reflecting facets may be parallel to each other and may be disposed at a first angle relative to a long axis of the first waveguide, the first aperture expander may be configured to receive the reflected first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide may be configured to receive the second portion of guided image beams and provide a transmitted second portion of guided image beams; and the second waveguide may further comprise a third diffraction grating configured to receive the transmitted second portion of guided image beams and provide a diffracted second portion of guided image beams; and a second aperture expander may be positioned in a second region that is laterally displaced from the first region, the second aperture expander may be configured to receive the diffracted second portion of guided image beams and may provide a second plurality of expanded image beams, wherein the second waveguide may be configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams; and a fourth stacked waveguide arrangement may include the first waveguide and may further include a first diffraction grating configured to receive the first portion of guided image beams and provide a diffracted first portion of guided image beams; and a first aperture expander may be positioned in a first region, the first aperture expander may include a second diffraction grating disposed in the first region, the first aperture expander may be configured to receive the diffracted first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide may be configured to receive the second portion of guided image beams and provide a transmitted second portion of guided image beams; and the second waveguide may further include a second mirror configured to receive the transmitted second portion of guided image beams and may provide a reflected second portion of guided image beams; and a second aperture expander may be positioned in a second region that may be laterally displaced from the first region, the second aperture expander may be configured to receive the reflected second portion of guided image beams and may provide a second plurality of expanded image beams, wherein the second waveguide may be configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams.

[0010] According to this example, the optical device wherein one of the reflected first portion of guided image beams and the diffracted first portion of guided image beams may be reflected within the first waveguide by total internal reflection between a first waveguide front surface and a first waveguide rear surface and wherein one of the diffracted second portion of guided image beams and the reflected second portion of guided image beams may be reflected within the second waveguide by total internal reflection between a second waveguide front surface and a second waveguide rear surface. According to this example, the optical device wherein the third waveguide may further include a third aperture expander positioned in a third region and configured to receive the transmitted first plurality of expanded image beams and the second plurality of expanded image beams and provide a third plurality of expanded image beams to exit a third waveguide rear surface.

[0011] According to this example, the optical device wherein the third aperture expander may include a third plurality of partially reflecting facets that may be parallel to each other and may be disposed at a third angle that may be oblique to a third waveguide front surface, and wherein the transmitted first plurality of expanded image beams and the second plurality of expanded image beams may be reflected by total internal reflection between a third waveguide front surface and the third waveguide rear surface. According to this example, the optical device wherein the first dimension may be orthogonal to the second dimension.

[0012] According to this example, the optical device may further include an input coupler configured to receive a collimated image beam from an image projector and to provide the first portion of guided image beams and to provide the second portion of guided image beams, wherein the input coupler may include a reflective internal surface, the input coupler may be configured to

receive the first portion of guided image beams having a first portion of sub-beams and a second portion of sub-beams, the input coupler may be configured to receive the second portion of guided image beams having a third portion of sub-beams and a fourth portion of sub-beams, the reflective internal surface configured to receive the first portion of sub-beams and provide a reflected first portion of sub-beams, the reflective internal surface may be configured to receive the third portion of sub-beams and provide a reflected third portion of sub-beams, wherein the first waveguide may be configured to receive the reflected first portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a first direction, the first waveguide may be configured to receive the second portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a second direction that may be opposite to the first direction, the reflected first portion of sub-beams and the second portion of sub-beams may be expanded to provide the first plurality of expanded image beams, wherein the second waveguide may be configured to receive the reflected third portion of sub-beams configured to propagate in a four-fold helical manner along the second waveguide and rotate in a first direction, the second waveguide may be configured to receive the fourth portion of sub-beams configured to propagate in a four-fold helical manner along the second waveguide and rotate in a second direction that may be opposite the first direction, the reflected third portion of sub-beams and the fourth portion of sub-beams being expanded to provide the second plurality of expanded image beams.

[0013] According to this example, the optical device may further include an image projector disposed adjacent to the input coupler and configured to provide a collimated image beam corresponding to an image field based on a digital image, the collimated image beam including the first portion of guided image beams corresponding to the first image field, the collimated image beam including the second portion of guided image beams corresponding to the second image field, wherein the collimated image beam may be collimated to infinity. According to this example, the optical device may further include a first input coupler configured to receive a first collimated image beam from a first image projector and to provide the first portion of guided image beams; and a second input coupler that may be configured to receive a second collimated image beam from a second image projector and to provide the second portion of guided image beams, wherein the first input coupler may include a first reflective internal surface, the first input coupler may be configured to receive the first portion of guided image beams having a first portion of sub-beams and a second portion of sub-beams, the reflective internal surface may be configured to receive the first portion of sub-beams and provide a reflected first portion of sub-beams, wherein the first waveguide may be configured to receive the reflected first portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a first direction, the first waveguide may be configured to receive the second portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a second direction that may be opposite to the first direction, the reflected first portion of sub-beams and the second portion of sub-beams may be expanded to provide the first plurality of expanded image beams, wherein the second input coupler may include a second reflective internal surface, the second input coupler may be configured to receive the second portion of guided image beams having a third portion of sub-beams and a fourth portion of sub-beams, the second reflective internal surface may be configured to receive the third portion of sub-beams and provide a reflected third portion of sub-beams, and wherein the second waveguide may be configured to receive the reflected third portion of sub-beams configured to propagate in a four-fold helical manner along the second waveguide and rotate in a first direction, the second waveguide may be configured to receive the fourth portion of sub-beams may be configured to propagate in a four-fold helical manner along the second waveguide and rotate in a second direction that may be opposite the first direction, the reflected third portion of sub-beams and the fourth portion of sub-beams may be expanded to provide the second plurality of expanded image beams.

[0014] According to this example, the optical device may further include a first image projector disposed adjacent to the first input coupler and configured to provide a first collimated image beam corresponding to the first image field based on at least a first portion of a digital image, the first collimated image beam including the first portion of guided image beams; and a second image projector disposed adjacent to the second input coupler and configured to provide a second collimated image beam corresponding to the second image field based on at least a second portion of the digital image, wherein the first collimated image beam and the second collimated image beam may be collimated to infinity.

[0015] According to this example, the optical device may further include at least one of: a first homogenizer disposed in a plane between a first waveguide top surface and a first waveguide bottom surface, and a second homogenizer disposed in a plane between a second waveguide top surface and a second waveguide bottom surface. According to this example, the optical device may further include at least one of: a first retarder waveplate disposed between a first waveguide bottom surface and a second waveguide top surface, the first retarder waveplate may be configured to receive at least one of the first plurality of expanded image beams and the transmitted second portion of guided image beams and to provide a first retarder output that may be at least one of rotated and depolarized; and a second retarder waveplate may be disposed between a second waveguide bottom surface and a third waveguide top surface, the second retarder waveplate may be configured to receive at least one of the second plurality of expanded image beams and the transmitted first plurality of expanded image beams and may provide a second retarder output that may be at least one of rotated and depolarized.

[0016] According to this example, the optical device may include at least one of: a first dielectric coating disposed on an input coupler bottom surface; a second dielectric coating disposed on a first waveguide bottom surface; and a third dielectric coating may be disposed on a second waveguide bottom surface. According to this example, the optical device may include at least one of: a frame may be configured to support the first waveguide, the second waveguide, and the third waveguide in relative position to each other, wherein the first waveguide and the second waveguide may be fully concealed within the frame; a first interface between an input coupler and the first waveguide may include a first air gap; a second interface between the first waveguide and the second waveguide includes a second air gap; and a third interface between the second waveguide and the third waveguide includes a third air gap.

[0017] The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative examples, aspects, embodiments, and features described above, further examples, aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description. In the drawings, like reference numbers indicate identical or functionally similar elements.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. 1 illustrates a block diagram of an optical system, in accordance with various examples of the present disclosure.

[0019] FIG. 2A illustrates a front plan view of an optical system including a light-guide, in accordance with various examples.

[0020] FIG. 2B illustrates a side plan view of an optical system including the light-guide of FIG. 2A, in accordance with various examples.

[0021] FIG. 3A illustrates a side plan view of an optical system including the light-guide of FIG. 2B, in accordance with various examples.

[0022] FIG. 3B illustrates a side plan exploded view of an optical system including the light-guide

of FIG. 3A, in accordance with various examples.

[0023] FIG. 3C illustrates a side plan view of an optical system including an alternative light-guide, in accordance with various examples.

[0024] FIG. 3D illustrates a side plan view of an optical system including an alternative light-guide, in accordance with various examples.

[0025] FIG. 4 illustrates a side plan view of an optical system including the light-guide of FIG. 3A, in accordance with various examples.

[0026] FIG. 5 illustrates a front plan view of image beams as applied to an input coupler, in accordance with various examples.

[0027] FIG. 6A illustrates a front plan view of an optical system including a light-guide, in accordance with various examples.

[0028] FIG. 6B illustrates a side plan view of an optical system including the light-guide of FIG. 6A, in accordance with various examples.

[0029] FIG. 7A illustrates a front plan view of an optical system including a light-guide, in accordance with various examples.

[0030] FIG. 7B illustrates a side plan view of an optical system including the light-guide of FIG. 7A, in accordance with various examples.

[0031] In the drawings, like reference numerals or characters indicate corresponding or like components.

DETAILED DESCRIPTION

[0032] In the following description, numerous specific details are set forth, such as particular structures, components, materials, dimensions, processing steps and techniques, in order to provide an understanding of the various embodiments of the present application. However, it will be appreciated by one of ordinary skill in the art that the various embodiments of the present application may be practiced without these specific details. In other instances, well-known structures or processing steps have not been described in detail in order to avoid obscuring the present application.

[0033] To be described in more detail below, a wearable device, such as a near eye display and/or smart glasses, can be implemented by a system and method described in accordance with the present disclosure and the various examples. The system can efficiently provide high quality optical information to a user in various applications.

[0034] FIG. 1 illustrates a block diagram of an optical system, in accordance with various examples of the present disclosure. Optical system **100** may include two or more devices or components. Optical system **100** may be implemented generally as a hybrid system including various electronic, optical, and electro-optical elements. An optical device **102** may include one or more elements from optical system **100**. To be described in more detail below, an optical system **100** may include a wearable device **110**, such as one or more near eye displays or smart glasses, which may be worn on or about the head of a user to convey optical information (e.g., a virtual image) to one or more eyes of a user. Both monocular and binocular applications are contemplated by the present disclosure. In various binocular implementations it is understood that some aspects of various elements related to power and/or processing may be shared.

[0035] Wearable device **110** may include a controller **112** with a memory **114** where controller **112** may be configured to send and receive electrical signals to various other elements in optical system **100**, to execute program instructions stored in memory **114** in order to process and provide information, to operate wearable device **110**, and to interact with other systems outside wearable device **110**, for example. Controller **112** may include a microcontroller, a processor, various discrete components, programmable logic devices, and/or various interface circuits that may access memory **114** which may be removable, replaceable, programmable, and reprogrammable to update instructions to controller **112**.

[0036] Wearable device **110** may also include a power management module **116** having a battery

118 (e.g., a battery module), where power management module **116** may be configured to charge, discharge, and monitor power usage for battery **118**. Various elements of wearable device **110** may receive power from battery **118**, including controller **112**, one or more image projectors **120** (e.g., a projecting optical device, or POD) having one or more digital image(s) **122**, and optical engine **142** may be configured to drive the one or more image projectors **120** to project the one or more digital image(s) **122**, for example.

[0037] Wearable device **110** may also include one or more image projectors **120**, each configured to produce a collimated image beam **124** (e.g., image illumination of a collimated image) based on a digital image **122**. The collimated image beam may be an illuminated representation of digital image **122** having an image field **126** which is a two-dimensional representation of digital image **122** based on either a single graphical image (e.g., a static image) or a sequence of graphical images (e.g., a moving image). The collimated image beam may be collimated to infinity (e.g., an image at infinity). Image field **126** may include a plurality of image sub-fields **126A-126F** corresponding to various regions of collimated image beam **124**, where each sub-field **126A-126F** may correspond to a plurality of different projection angles. For example, collimated image beam **124** may be composed of image field **126A** corresponding to a first half of collimated image beam **124**, image field **126D** corresponding to a second half of collimated image beam **124**. Image field **126A** may further comprise a first portion **126B** and a second portion **126C**. Image field **126D** may further comprise a third portion **126E** and a fourth portion **126F**.

[0038] Wearable device **110** may also include one or more light-guides **130**, each including two or more light-guide optical elements **132** (e.g., LOEs) which may be denoted as waveguides (e.g., WGs). As used herein, the terms or phrases light-guide, light-guide optical element, and waveguide are related, and in some ways may be considered synonymous. Each light-guide optical element **132** may include one or more transparent material components configured to receive and propagate light, where light may enter into and exit from various external and internal surfaces of the one or more transparent material components. For example, the light-guide optical elements **132** may include optical glass or other suitable material that is transformed into various complex optical structures using a process that may include coating, stacking, slicing, polishing, and shaping the transparent materials. The process may also include the addition of partially reflective or fully reflective materials such as mirror coatings and one or more homogenizing elements on the surface of or within one or more of the light-guide optical elements **132**, for example. Light-guide **130** may also include one or more passive optical elements **134** such as one or more input couplers or one more retarder waveplates, for example.

[0039] Wearable device **110** may also include one or more optical engines **142** coupled to the one or more image projectors **120** and one or more light-guides **130**. Optical engine **142** may be configured to directly operate image projector **120** under the direction of the controller **112**. For example, optical engine **142** may provide graphics processing for the digital image before projection of an illuminated representation of the one or more digital image(s) **122** by image projector **120**.

[0040] Wearable device **110** may also include a frame **148** (e.g., a structure) for supporting and retaining two or more light-guide optical elements **132** (e.g., a first waveguide, a second waveguide, and a third waveguide) in relative position to each other in wearable device **110**. For example, frame **148** may support and retain a first image projector **120** in position next to a first light-guide optical element **132**. Similarly, frame **148** may support and retain a second image projector **120** in position next to a second light-guide optical element **132**. In this manner, frame **148** may support and retain one or two image projector **120** and light-guide **130** pairs worn on or about the head of a user configured to provide a virtual image to one or both eyes of a user. References are made herein regarding the orientation of various elements relative to each other. Such references may also include reference to various elements of wearable device **110** when supported by frame **148** or in reference to a three-dimensional (3D) reference (e.g., X, Y, Z axes),

as described in the relevant drawing figure.

[0041] Optical system **100** may also include a host computer **170** that may include a processor **174** configured to read and execute operations based on instructions **178** stored in a computer-readable medium **180**. Instructions **178** may include at least some instructions provided to controller **112** and stored in memory **114**. Host computer **170** may communicate with one or more elements of wearable device **110** over a bus **188** to send and/or receive power, status, control, and image information. In this manner, host computer **170** may provide power to charge battery **118**, provide instructions to and receive status from controller **112** and various other elements of wearable device **110**, and to provide data based on digital image **122** to optical engine **142**.

[0042] FIG. 2A illustrates a front plan view of an optical system including a light-guide, in accordance with various examples. FIG. 2B illustrates a side plan view of an optical system including the light-guide of FIG. 2A, in accordance with various examples. As will be described more fully below, in various examples the present disclosure describes a pair of cascaded, or double-stacked rectangular waveguides, where each waveguide receives a portion of an input image field (e.g., roughly half), and where two sub-portions of each portion of an input image field may advance and be reflected within each waveguide by four-fold internal reflection while rotating in opposite directions (e.g., in a helical manner) within the waveguide, and where the two portions of the reflected and rotated input image fields may then both be coupled into a third waveguide and projected (e.g., outcoupled) as a virtual image to an eye of a user. Cascading two rectangular light-guides, optionally with low-refractive index materials, may enable transmission of a wider field of view (FoV) where each individual rectangular light-guide transmits only a portion of the final image, yet the portions of the final image are coupled into a third light-guide optical element, for example. FIG. 1 through FIG. 2B illustrates an optical system **100** that may include an optical device **202** with one or more optical elements of optical system **100**. Optical device **202** may be similar in some ways to optical device **102** illustrated in FIG. 1. Optical device **202** may include a light-guide **130** with two or more light-guide optical elements **132**.

[0043] According to an example, optical device **202** may include an input coupler **220** (e.g., a wedge-shaped coupling prism) configured to receive a collimated image beam **206** from an image projector **120** and configured to provide both a first portion of guided image beams **208** and a second portion of guided image beams **214**. First portion of guided image beams **208** and second portion of guided image beams **214** may be separated into two halves by a first dividing plane **226** (e.g., corresponding to a YZ-plane, but represented as a line **226** in FIG. 2A) which bisects input coupler **220** in a left-right manner, as shown. Optical device **202** may include a first waveguide **230** that may have a first mirror **232** configured to receive (e.g., or couple-in) first portion of guided image beams **208** and provide a reflected first portion of guided image beams **234**. First waveguide **230** may have a first aperture expander **240** positioned in a first region **242**. First aperture expander **240** may include a plurality of partially reflecting facets **246** that may be mutually parallel to each other and to first mirror **232** and may be inclined at a first angle **239** relative to X-axis **294** (e.g., horizontal axis of first waveguide **230**). A partially reflecting facet may be embedded within first waveguide **230** and implemented as a partially reflective mirror surface and may also be denoted as an embedded partial plane reflector, for example. First angle **239** may range from about 20° to 60° degrees and may correspond to a dynamic range that may depend on a reflection architecture of the facets. United States Patent Publication 20190064518 titled “Aperture Multiplier Using a Rectangular Waveguide”, and assigned to Applicant, describes various details related to image rays propagating relative to partially reflecting internal facets in waveguides, for example. As used herein, the terms aperture expander, aperture expansion, and aperture multiplication to produce an expanded image beam may be considered equivalent with each other. First mirror **232** and first plurality of partially reflecting facets **246** being mutually parallel may result in greater tolerance of mechanical shift during the manufacturing process. Each of partially reflective facets **246** may have a reflectivity that is constant. Alternatively, the reflectivity of partially reflecting facets **246** may

either increase or decrease in a direction away from first mirror **232** depending on the application. First aperture expander **240** may be configured to receive reflected first portion of guided image beams **234** and provide a first plurality of expanded image beams **248**. First waveguide **230** may be configured to receive second portion of guided image beams **214** and provide a transmitted second portion of guided image beams **244**. First portion of guided image beams **208** and second portion of guided image beams **214** may each correspond to substantially half of the projected image beam **206** from image projector **120**, but other proportions may be used. Although FIG. 2A illustrates a gap between image projector **120** and input coupler **220**, such a gap is for illustrative purposes and no gap may exist in an actual implementation, for this example and others. Thus, a half-image provided by first portion of guided image beams **208** may fill an available angular range within first waveguide **230**.

[0044] Optical device **202** may include a second waveguide **250** having a second mirror **252** configured to receive transmitted second portion of guided image beams **244** and provide a reflected second portion of guided image beams **254**. As described, first mirror **232** and second mirror **252** may be a fully reflective mirrors or partially reflective mirrors. First mirror **232** may have a different reflectivity compared with second mirror **252** to compensate for loss of light energy from first waveguide **230** through second waveguide **250**, for example. Also, first mirror **232** may be partially reflective in the case that some portion of first mirror **232** overlaps laterally with (e.g., partially obscures) second mirror **252**, for example. Second waveguide **250** may have a second aperture expander **260** positioned in a second region **262** that is laterally displaced **264** from first region **242**.

[0045] Second aperture expander **260** may include a second plurality of partially reflecting facets **266** disposed in second region **262**, where second plurality of partially reflecting facets **266** and second mirror **252** may be parallel to each other and disposed at second angle **259** which may be different from first angle **239**. As above, second mirror **252** and second plurality of partially reflecting facets **266** being parallel may result in greater tolerance of mechanical shift during the manufacturing process. Similar to first angle **239**, second angle **259** may also range from about 20° to 60° degrees and may correspond to a dynamic range that may depend on a reflection architecture of the facets. However, there may be a difference between first angle **239** and second angle **259** where the beams propagating along the respective waveguides may be propagating at the same angle even though they may originate from different angles as injected from image projector **120**. For example, for a large field in a glass-like medium having a dynamic range of about 40 degrees (e.g., about 60 degrees in air), a difference between respective centers of two different field sections, such as first portion of guided image beams **208** and second portion of guided image beams **214**, may have a dynamic range of approximately half, or about 20 degrees. In this example using mirror reflectors, the difference between the mirror angles for first angle **239** and second angle **259** may be about 10 degrees.

[0046] A first technical benefit of first angle **239** being different from second angle **259** may include an improved light homogenization and virtual image reproduction by avoiding image stitching, for example. A second technical benefit of having first angle **239** different from second angle **259** may include intensity compensation where the second angle **259** provides greater energy reflection capability after traversing a greater distance between second mirror **252** and second aperture expander **260** as compared with first mirror **232** and first aperture expander **240**. Second aperture expander **260** may be configured to receive reflected second portion of guided image beams **254** and provide a second plurality of expanded image beams **268**. Second waveguide **250** may be configured to receive first plurality of expanded image beams **248** and provide a transmitted first plurality of expanded image beams **278**. Thus, a half-image provided by first portion of guided image beams **214** may fill an available angular range within second waveguide **250**. Reflection from and transmission through input coupler **220** may enable total internal reflection (TIR) from first waveguide front surface **231** and first waveguide rear surface **233**.

Reflection from first mirror **232** may enable total internal reflection from first waveguide top surface **235** and first waveguide bottom surface **237**. Reflection from second mirror **252** may enable total internal reflection from second waveguide top surface **255** and second waveguide bottom surface **257**.

[0047] First aperture expander **240** and second aperture expander **260** may overlap laterally (e.g., horizontally as shown) by an overlap distance **290** that may range from between, for example, 1% to 20% of a length of first waveguide **230** and second waveguide **250**, which may be preferably equal in length. Overlap distance **290** may preferably range from between 5% to 10% of the length of first waveguide **230**. A technical benefit of first aperture expander **240** and second aperture expander **260** overlapping may promote continuity of the combined image, for example.

Alternatively, first aperture expander **240** and second aperture expander **260** may not overlap, so the overlap distance **290** may be zero where image continuity is not an issue. As an alternative, the order (e.g., sequence of light processing) of first waveguide **230** and second waveguide **250** may be reversed. Further, another rectangular waveguide, similar to both first waveguide **230** and second waveguide **250**, may also be used and may include another aperture expander that spans some or all of a lateral region of first aperture expander **240** and second aperture expander **260**, for example. In yet another alternative, a separate, possibly smaller image projector **120**, along with or without a separate coupling-in prism **220** may be used for each rectangular waveguide. When used without a separate coupling-in prism, each separate, projector **120** may be oriented at an appropriate angle relative to the respective waveguide to inject an input image beam **206** (or portion thereof) to induce four-fold internal reflection along the respective waveguide, as described.

[0048] Optical device **202** may include a third waveguide **270** (e.g., a “slab”) with a third aperture expander **272** (e.g., oriented vertically) positioned in a third region **274** and configured to receive transmitted first plurality of expanded image beams **278** (e.g., guided-transmitted first plurality of expanded image beams **278**) and second plurality of expanded image beams **268** and provide a third plurality of expanded image beams **280** to exit a third waveguide rear surface **273** toward an eye box **282** (e.g., an out-coupling region) and an eye **284** of a user or wearer of wearable device **110**. A guided-transmitted beam may be distinguished from free-space transmitted beam that may be transmitted between optical components, for example. Third aperture expander **272** may include a third plurality of partially reflecting facets **276** that may be mutually parallel to each other and may be inclined at a third angle **279** relative to Y-axis **296** (e.g., vertical axis of third waveguide **270**) and that is oblique to third waveguide front surface **271**. For completeness, Z-axis **298** corresponds to direction that is perpendicular to an XY-plane.

[0049] Lateral (or vertical) aperture expansion may also be denoted as aperture multiplication. Thus, first waveguide **230**, second waveguide **250**, and third waveguide **270** together provide a two-dimensional (2-D) expansion of input image beam **206** from image projector **120**. In this manner, first waveguide **230**, second waveguide **250**, and third waveguide **270** may be configured to receive and continuously reflect guided image beams to provide expanded image beams. Third plurality of partially reflecting facets **276** may be perpendicular to a YZ-plane. Alternatively, third plurality of partially reflecting facets **276** may be inclined obliquely relative to both a YZ-plane and a set of elongated parallel external faces of third waveguide **270**, such as third waveguide front surface **271** and third waveguide rear surface **273**, for example. United States Patent Publication 20190064518, mentioned above, also describes how a waveguide may be illuminated using a single polarization (e.g., preferably s-polarization) with an orientation orthogonal to the waveguide surfaces, for example.

[0050] For various examples disclosed herein, first waveguide **230** may include a first waveguide front surface **231** and a first waveguide rear surface **233** that are parallel to each other. First waveguide **230** may also include a first waveguide top surface **235** and a first waveguide bottom surface **237** that are parallel to each other. Similarly, for various examples disclosed herein, second waveguide **250** may include a second waveguide front surface **251** and a second waveguide rear

surface **253** that are parallel to each other. Second waveguide **250** may also include a second waveguide top surface **255** and a second waveguide bottom surface **257** that are parallel to each other. In this manner, the mutually parallel, opposite sides, and mutually parallel opposite top and bottom surfaces for each of the first waveguide **230** and second waveguide **250**, may together describe a rectangular waveguide.

[0051] First waveguide **230** partially reflecting facets **246** may be perpendicular to first waveguide front surface **231**, while second waveguide **250** partially reflecting facets **266** may be perpendicular to second waveguide front surface **251**, for example. Alternatively, first plurality of partially reflecting facets **246** may be inclined obliquely relative to both sets of elongated parallel external faces of first waveguide **230**, such as first waveguide front surface **231** and first waveguide rear surface **233** and/or first waveguide top surface **235** and first waveguide bottom surface **237**, for example. Similarly, second plurality of partially reflecting facets **266** may be inclined obliquely relative to both sets of elongated parallel external faces of second waveguide **250**, such as second waveguide front surface **251** and second waveguide rear surface **253** and/or second waveguide top surface **255** and first waveguide bottom surface **257**, for example. First waveguide bottom surface **237** may be disposed adjacent to second waveguide top surface **255**.

[0052] Third waveguide **270** may include a third waveguide front surface **271** and third waveguide rear surface **273** that are parallel to each other. Third waveguide **270** may also include a third waveguide top surface **275** that may be disposed adjacent to second waveguide bottom surface **257**. A bottom contour **277** of third waveguide **270** may have the form of an isosceles trapezoid but could also be smoothly curved, squared off, or the like. Thus, the sides (e.g., left-right sides shown in FIG. 2A) and bottom surface of third waveguide **270** may not be involved in the operation of light-guide **130**. As illustrated in FIG. 2B, light-guide **130** may include a first interface **213** disposed between input coupler **220** and first waveguide **230**, a second interface **215** disposed between first waveguide **230** and second waveguide **250**, and a third interface **217** disposed between second waveguide **250** and third waveguide **270**. Each of first interface **213**, second interface **215**, and third interface **217** may include an air gap of separation, a coating, or a passive optical element **134** such as a polarizer disposed in the interface, where these interface-mediums may preserve the total internal reflection (TIR) of the four-fold propagation in their associated rectangular waveguide. As shown in FIG. 2A-2B, first waveguide **230** may include reflective elements and second waveguide **250** may include reflective elements. Thus, optical device **202** and light-guide **130** may comprise a first stacked waveguide arrangement of a reflective type.

[0053] FIG. 3A illustrates a side plan view of an optical system including the waveguide of FIG. 2B, in accordance with various examples. FIG. 3B illustrates a side plan exploded view of an optical system including the waveguide of FIG. 3A, in accordance with various examples. FIG. 3C illustrates a side plan view of an optical system including an alternative waveguide, in accordance with various examples. FIG. 3D illustrates a side plan view of an optical system including an alternative waveguide, in accordance with various examples. According to an example, a thickness **330** of first waveguide **230**, second waveguide **250**, and third waveguide **270** may be substantially equal. However, a relative height of first waveguide **230** compared with a height of second waveguide **250** may vary. Further, first waveguide front surface **231**, second waveguide front surface **251**, and third waveguide front surface **271** may be co-planar with each other. Hence, with an equal thickness and front surfaces being co-planar, it is understood that first waveguide rear surface **233**, second waveguide rear surface **253**, and third waveguide rear surface **273** may also be co-planar with each other. A technical benefit of equal thicknesses and co-planarity for first waveguide **230**, second waveguide **250**, and third waveguide **270** may include minimizing power loss in transmission of light between adjacent waveguides, for example. As described, each of the first waveguide **230**, second waveguide **250**, and third waveguide **270** have parallel front and rear surfaces so that light propagating and reflecting within each of the waveguides may be reflected by total internal reflection (TIR) between the corresponding front and rear surfaces within each of the

waveguides.

[0054] First guided image beams **234** may be reflected within first waveguide **230** by total internal reflection between first waveguide front surface **231** and first waveguide rear surface **233** and the reflected light may exit first waveguide **230** at first waveguide bottom surface **237**, for example. Because the first plurality of partially reflecting facets **246** is parallel to first mirror **232**, light beams may couple out of first waveguide **230** at the same angle coupled in from input coupler **220**, for example. Similarly, reflected second portion of guided image beams **254** may be reflected within second waveguide **250** by total internal reflection between second waveguide front surface **251** and second waveguide rear surface **253** and the reflected light may exit second waveguide **250** at second waveguide bottom surface **257**, for example. Finally, transmitted first plurality of expanded image beams **248** and second plurality of expanded image beams **268** may be reflected by total internal reflection between third waveguide front surface **271** and third waveguide rear surface **273**, and the reflected light may exit third waveguide rear surface **273** after reflection from third aperture expander **272**.

[0055] In one example, FIG. **3A** illustrates light-guide **130** may include first interface **213** disposed between input coupler **220** and first waveguide **230**, second interface **215** disposed between first waveguide **230** and second waveguide **250**, and third interface **217** disposed between second waveguide **250** and third waveguide **270**. Each of first interface **213**, second interface **215**, and third interface **217** may include an air gap of separation, a coating, or a passive optical element **134** such as a polarizer disposed in the interface. Total internal reflection (TIR) guidance within first waveguide **230** and second waveguide **250** may be improved by the application of various optical coatings, presence of an airgap, and or the use of low-refractive index material above or below first waveguide **230** and/or second waveguide **250**.

[0056] FIG. **3B** illustrates a side plan exploded view of an optical system including the light-guide of FIG. **3A**, in accordance with various examples. An input coupler bottom surface **227** may include a first coating **302**, first waveguide top surface **235** may include a second coating **306**, first waveguide bottom surface **237** may include a third coating **310**, second waveguide top surface **255** may include a fourth coating **314**, second waveguide bottom surface **257** may include a fifth coating **318**, and third waveguide top surface **275** may include a sixth coating **322**. Each of the coatings may be uniform across the surface of the relevant portions and may include at least one layer of a dielectric coating, a dielectric reflective coating, a varying reflective coating, or a partially transmissive mirror coating which may have a polarization dependency.

[0057] FIG. **3C** illustrates a side plan view of an optical system including an alternative light-guide, in accordance with various examples. A retarder waveplate is a passive optical element **134** that may be composed of birefringent, crystalline, or polymer materials that may be used to create a phase shift between polarization components in a light beam. A retarder waveplate may be used to at least one of rotate and depolarize a light beam passing through the retarder waveplate without attenuating, deviating, or displacing the light beam. As illustrated in FIG. **3C**, a first retarder waveplate **304** may be disposed at first interface **213** between at least a portion of the region between input coupler bottom surface **227** and first waveguide top surface **235** and configured to at least one of rotate and depolarize at least some portion of the light passing from input coupler **220** to first waveguide **230**. A second retarder waveplate **312** may be disposed at second interface **215** between at least a portion of the region between first waveguide bottom surface **237** and second waveguide top surface **255** and configured to at least one of rotate and depolarize at least some portion of the light passing from first waveguide **230** to second waveguide **250**. Finally, a third retarder waveplate **320** may be disposed at third interface **217** between at least a portion of the region between second waveguide bottom surface **257** and third waveguide top surface **275** and configured to at least one of rotate and depolarize at least some portion of the light passing from second waveguide **250** to third waveguide **270**. Second retarder waveplate **312** may be used to reorient light reflected from first plurality of partially reflecting facets **246** and/or third retarder

waveplate **320** may be used to reorient light reflected from either/both first plurality of partially reflecting facets **246** and second plurality of partially reflecting facets **266** to fit polarization needed for third plurality of partially reflecting facets **276**, in some applications.

[0058] FIG. **4** illustrates a side plan view of an optical system including the waveguide of FIG. **3A**, in accordance with various examples. In reference to FIG. **2A** through FIG. **4**, input coupler **220** may have a reflective internal surface **408** (e.g., a reflective internal face) and be configured to receive the first portion of guided image beams **208** with a first portion of sub-beams **210** and a second portion of sub-beams **212**. Input coupler **220** may also be configured to receive second portion of guided image beams **214** with a third portion of sub-beams **216** and a fourth portion of sub-beams **218**. Reflective internal surface **408** may be disposed on a rear surface **223** of input coupler **220** as shown in FIGS. **3A-3C** and FIG. **4** and may be configured to receive first portion of sub-beams **210** and provide a reflected first portion of sub-beams **410**. Alternatively, as shown in reference to FIG. **3D**, reflective internal surface **408** may be disposed on a front surface **221** of input coupler **220** when input coupler **220** is rotated 180-degrees so that image projector **120** may be mounted in a symmetrically opposite orientation, for example.

[0059] Reflective internal surface **408** may be configured to receive third portion of sub-beams **216** and provide a reflected third portion of sub-beams **416**. Further, second portion of sub-beams **212** and fourth portion of sub-beams **218** may be configured to pass through input coupler **220** without reflecting from reflective internal surface **408**. In this manner, reflected first portion of sub-beams **410** and un-reflected second portion of sub-beams **412** may exit input coupler bottom surface **227** at different predetermined angles and enter first waveguide top surface **235** at substantially the same exiting angles because input coupler bottom surface **227** is substantially parallel to first waveguide top surface **235**. As described in reference to FIG. **2A**, first portion of guided image beams **208** and second portion of guided image beams **214** may be separated into two halves by a first dividing plane **226** which bisects input coupler **220** in a left-right manner, as shown. Similarly, FIG. **4** illustrates first portion of sub-beams **210** and second portion of sub-beams **212** may be further separated by a second dividing plane **426** (e.g., corresponding to a plane that includes X-axis **294**, but represented as a line **426** in FIG. **4**) which bisects first portion of guided image beams **208** into a top-half **404** (e.g., back half) with first portion of sub-beams **210** and a bottom-half **406** (e.g., front half) with sub-beams **212**.

[0060] Reflected first portion of sub-beams **410** may enter first waveguide top surface **235** and be reflected from first mirror **232** inclined at a first angle **239** relative to X-axis **294** (e.g., horizontal axis of first waveguide **230**) to become reflected first portion of sub-beams **236** rotating in a first direction **432**, and second portion of sub-beams **412** may enter first waveguide top surface **235** and be reflected from first mirror **232** to become reflected second portion of sub-beams **238** rotating in a second direction **434** which may be opposite to first direction **432**. In this manner, due to coupling of an image **206** from image projector **120** through input coupler **220** which is inclined at a coupling angle **229**, then reflecting a first half of the coupled image at a first angle **239** and a second half of the coupled image at a second angle **259**, an initial direction of propagation at a coupling angle that may be oblique to opposite pairs of parallel faces of first waveguide **230** may cause the coupled-in image to advance by four-fold internal reflection along first waveguide **230**. Thus, reflected first portion of sub-beams **236** and reflected second portion of sub-beams **238** may be propagated within first waveguide **230** in substantially opposite directions while traversing the length of first waveguide **230** in a direction away from first mirror **232** in what may be described as a four-fold, helical (e.g., helix) or a corkscrew-like manner.

[0061] United States Patent Publication 20190064518, mentioned above, also describes various details related to four-fold internal reflection in an elongated waveguide, for example. In this manner, an image from an image projector may be coupled into an optical waveguide with an initial direction of propagation at a coupling angle that is oblique to opposite pairs of parallel faces so the image advances by four-fold internal reflection along the waveguide. In the presently

described examples, the propagated image beams may be then coupled into an adjacent waveguide. First aperture expander **240** may include a first plurality of partially reflecting facets **246** disposed in first region **242**. As reflected first portion of sub-beams **236** and reflected second portion of sub-beams **238** propagate in a direction away from first mirror **232** in a four-fold, helical manner, reflected first portion of sub-beams **236** and reflected second portion of sub-beams **238** may enter first region **242** and be reflected by first aperture expander **240** to provide first plurality of expanded image beams **248** configured to exit from first waveguide bottom surface **237**. Thus, reflected first portion of sub-beams **236** and reflected second portion of sub-beams **238** may be expanded in a first dimension (e.g., X-axis **294** direction).

[0062] Reflected third portion of sub-beams **416** and un-reflected fourth portion of sub-beams **418** may exit input coupler bottom surface **227** at different predetermined angles and enter first waveguide top surface **235** at substantially the same exiting angles because input coupler bottom surface **227** is substantially parallel to first waveguide top surface **235**. As mentioned above, first waveguide **230** may be configured to receive second portion of guided image beams **214**, comprising reflected third portion of sub-beams **416** and fourth portion of sub-beams **418**, and provide a transmitted second portion of guided image beams **244** which passes through first waveguide **230** from first waveguide top surface **235** to first waveguide bottom surface **237** while being reflected by total internal reflection between first waveguide front surface **231** and first waveguide rear surface **233** and may exit from first waveguide bottom surface **237** at different predetermined angles and enter second waveguide top surface **255** at substantially the same exiting angles because first waveguide bottom surface **237** is substantially parallel to second waveguide top surface **255**.

[0063] Transmitted second portion of guided image beams **244** may pass through first waveguide **230** in a region adjacent to first mirror **232**, where some portion of transmitted second portion of guided image beams **244** (e.g., derived from second portion of guided image beams **214**) may overlap in region **292** and be reflected by first mirror **232** to address image overlap. Alternatively, none of transmitted second portion of guided image beams **244** may overlap or be reflected by first mirror **232**, so that first mirror **232** only reflects first portion of guided image beams **208** and does not reflect any of second portion of guided image beams **214** where image overlap may not be an issue.

[0064] Transmitted second portion of guided image beams **244** (derived from reflected third portion of sub-beams **416** and un-reflected fourth portion of sub-beams **218**) may enter second waveguide top surface **255** and be reflected from second mirror **252** inclined at a second angle **259** relative to X-axis **294** ((e.g., long axis of second waveguide **250**)) to become reflected third portion of sub-beams **256** rotating in a first direction **452**, and fourth portion of sub-beams **218** may enter second waveguide top surface **255** and be reflected from first mirror **232** to become reflected fourth portion of sub-beams **258** rotating in a second direction **454** which may be opposite to first direction **452**. Thus, reflected third portion of sub-beams **256** and reflected fourth portion of sub-beams **258** may be propagated within second waveguide **250** in substantially opposite directions while traversing the length of second waveguide **250** in a direction away from second mirror **252** in a four-fold, helical manner.

[0065] As reflected third portion of sub-beams **256** and reflected fourth portion of sub-beams **258** propagate in a direction away from second mirror **252** in a four-fold, helical manner, reflected third portion of sub-beams **256** and reflected second portion of sub-beams **258** may enter second region **262** and be reflected by second aperture expander **260** to provide second plurality of expanded image beams **268** configured to exit from second waveguide bottom surface **257**. As reflected third portion of sub-beams **256** and reflected fourth portion of sub-beams **258** propagate in a direction away from second mirror **252** in a four-fold, helical manner, reflected third portion of sub-beams **256** and reflected fourth portion of sub-beams **258** may enter second region **262** and be reflected by second aperture expander **260** to provide second plurality of expanded image beams **268**

configured to exit from second waveguide bottom surface **257**. Thus, reflected third portion of sub-beams **256** and reflected fourth portion of sub-beams **258** may be expanded in a first dimension (e.g., X-axis **294** direction).

[0066] First waveguide **230** may include a first homogenizer **286** disposed in a parallel plane disposed vertically about midway between first waveguide top surface **235** and first waveguide bottom surface **237**, and disposed horizontally (e.g., laterally) between first mirror **232** and a first partially reflective facet **246** of first aperture expander **240**. Similarly, second waveguide **250** may include a second homogenizer **288** disposed in a parallel plane disposed vertically about midway between second waveguide top surface **255** and second waveguide bottom surface **257**, and disposed horizontally (e.g., laterally) between second mirror **252** and a first partially reflective facet **266** of second aperture expander **260**. Various light homogenizers may be used, alone or in combination with each other, to provide improved illumination uniformity, among other benefits. Homogenizers (**286**, **288**) may comprise a partial plane reflector as a semi-reflective surface, a partially transmissive surface, or film added within the corresponding waveguide (**230**, **250**). When present, a transmissive homogenizer disposed within a waveguide may effectively double the number of reflected beams by reflecting incident light beams traversing the waveguide in an ascending or descending manner. By ascending, some portion of light from below the homogenizer may reflect off a homogenizer lower surface and a remaining portion of the ascending light beam may pass through the homogenizer, effectively doubling the number of light beams. By descending, some portion of light from above the homogenizer may reflect off a homogenizer upper surface, and a remaining portion of the descending light beam may pass through the homogenizer, effectively doubling the number of light beams.

[0067] According to an example, optical system **100** may include a frame **148** (e.g., a structural element) configured to support wearable device **110**, two or more of controller **112**, memory **114**, power management module **116**, battery **118**, image projector **120**, light-guide **130** including two or more light-guide optical elements **132** such as first waveguide **230**, second waveguide **250**, third waveguide **270**, optical engine **142**, first waveguide **230**, second waveguide **250**, and third waveguide **270** in relative position to each other. In an example, frame **148** may support input coupler **220** and first waveguide **230** so that a first interface **213** between input coupler **220** and first waveguide **230** includes a first air gap. In an example, frame **148** may support first waveguide **230** and second waveguide **250** so that a second interface **215** between first waveguide **230** and second waveguide **250** includes a second air gap. In an example, frame **148** may support second waveguide **250** and third waveguide **270** so that a third interface **217** between second waveguide **250** and third waveguide **270** includes a third air gap. In an example, frame **148** may support first waveguide **230** and second waveguide **250** so that first waveguide **230** and second waveguide **250** may be fully concealed within frame **148**, for example.

[0068] FIG. 5 illustrates a front plan view of image beams as applied to an input coupler, in accordance with various examples. In reference to FIG. 4 and FIG. 5, an input face **225** of input coupler **220** may be divided into four quadrants by first dividing plane **226** and second dividing plane **426**. As shown, image beam **206** from image projector **120** may be directed to input face **225** of input coupler **220** at an intersection of first dividing plane **226** and second dividing plane **426**. First portion of guided image beams **208** corresponding to first portion of sub-beams **210** may be directed at least partially to a reflective internal face of input coupler rear surface **223** to reflect back into input coupler **220** as reflected first portion of sub-beam **410** and enter first waveguide **230** at first mirror **232** as reflected first portion of sub-beams **236** at a predetermined angle depending on the origin of the image pixel image field corresponding to image beams at first quadrant Q1. First portion of guided image beams **208** corresponding to second portion of sub-beams **212** may be directed to pass through input coupler bottom surface **227** and enter first waveguide **230** at first mirror **232** as reflected second portion of sub-beams **238** at another predetermined angle depending on the origin of the image pixel image field corresponding to image

beams at second quadrant Q2. Similarly, second portion of guided image beams **214** corresponding to third portion of sub-beams **216** may be directed at least partially to a reflective internal face of input coupler rear surface **223** to reflect back into input coupler **220** as reflected third portion of sub-beam **416** and enter first waveguide **230** adjacent to first mirror **232** as a first portion of transmitted second portion of guided image beams **244** at a predetermined angle depending on the origin of the image pixel image field corresponding to image beams at first quadrant Q3. Second portion of guided image beams **214** corresponding to second portion of sub-beams **218** may be directed to pass through input coupler bottom surface **227** and enter first waveguide **230** adjacent to first mirror **232** as a second portion of transmitted second portion of guided image beams **244** at another predetermined angle depending on the origin of the image pixel image field corresponding to image beams at second quadrant Q4.

[0069] According to an example, an optical system **100** may include an image projector **120** configured to produce a collimated image beam **206** based on a digital image **122**, wherein the collimated image beam may be collimated to infinity. Optical system **100** may include an input coupler **220** configured to receive collimated image beam **206** from image projector **120** and configured to provide both a first portion of guided image beams **208** and a second portion of guided image beams **214**. As will be described more fully below, first portion of guided image beams **208** may include a first portion of sub-beams **210** and a second portion of sub-beams **212**. Further, second portion of guided image beams **214** may include a third portion of sub-beams **216** and a fourth portion of sub-beams **218**.

[0070] Optical system **100** may include a first waveguide **230** with a first mirror **232** that may be configured to receive the first portion of guided image beams **208** and provide a reflected first portion of guided image beams **234**. First waveguide may have a first aperture expander **240** positioned in a first region **242**. First aperture expander **240** may be configured to receive the reflected first portion of guided image beams **234** and provide a first plurality of expanded image beams **248**, where reflected first portion of guided image beams **234** may be expanded laterally along X-axis **294** to provide a first plurality of expanded image beams **248** that may exit from first waveguide bottom surface **237**, for example. First waveguide **230** may be configured to receive second portion of guided image beams **214** and provide a transmitted second portion of guided image beams **244**.

[0071] Optical system **100** may include a second waveguide **250** with a second mirror **252** that may be configured to receive the transmitted second portion of guided image beams **244** and provide a reflected second portion of guided image beams **254**. Second waveguide **250** may have a second aperture expander **260** positioned in a second region **262** that may be laterally displaced **264** from first region **242**. Second aperture expander **260** may be configured to receive reflected second portion of guided image beams **254** and provide a second plurality of expanded image beams **268**, where reflected second portion of guided image beams **254** may be expanded laterally along X-axis **294** to provide a second plurality of expanded image beams **268** that may exit from second waveguide bottom surface **257**, for example. Second waveguide **250** may be configured to receive first plurality of expanded image beams **248** and provide a transmitted first plurality of expanded image beams **278** to exit from second waveguide bottom surface **257**.

[0072] Optical system **100** may include a third waveguide **270** that may have a third aperture expander **272** (e.g., oriented vertically) positioned in a third region **274** configured to receive transmitted first plurality of expanded image beams **278** and second plurality of expanded image beams **268** and provide a third plurality of expanded image beams **280** to exit a third waveguide rear surface **273** toward an eye box **282** and an eye **284** of a user or wearer of wearable device **110**. Third aperture expander **272** may include a plurality of partially reflecting facets **276** that may be mutually parallel to each other and may be inclined at a third angle **279** relative to Y-axis **296** (e.g., vertical axis of third waveguide **270**) and that is oblique to third waveguide front surface **271**, where transmitted first plurality of expanded image beams **248** and second plurality of expanded

image beams **268** may be expanded vertically along Y-axis **296**, for example. In some examples, a light-guide **130** may include passive and active optical components as various light-guide optical elements **132** (LOEs), including input coupler **220**, first waveguide **230**, second waveguide **250**, and third waveguide **270**.

[0073] FIG. **6A** illustrates a front plan view of an optical system including a light-guide, in accordance with various examples. FIG. **6B** illustrates a side plan view of an optical system including the light-guide of FIG. **6A**, in accordance with various examples. Image beam propagation in FIGS. **6A-6B** may be analogous to the beam propagation described in reference to FIG. **1** through FIG. **5**, where corresponding reference numbers may indicate corresponding functions.

[0074] According to an example, an optical device **602** may include an input coupler **220** configured to receive a collimated image beam **206** from an image projector **120** and to provide both a first portion of guided image beams **208** and a second portion of guided image beams **214**. Optical device **602** may be similar in some ways to optical device **102** illustrated in FIG. **1** and optical device **202** illustrated in FIGS. **2A-2B**. In reference to FIG. **2A** through FIG. **4**, input coupler **220** may have a reflective internal surface **408** (e.g., a reflective internal face) and be configured to receive the first portion of guided image beams **208** with a first portion of sub-beams **210** and a second portion of sub-beams **212**. Input coupler **220** may also be configured to receive second portion of guided image beams **214** with a third portion of sub-beams **216** and a fourth portion of sub-beams **218**. Reflective internal surface **408** may be disposed on a rear surface **223** of input coupler **220** as shown in FIG. **3A** through FIG. **6B** and may be configured to receive first portion of sub-beams **210** and provide a reflected first portion of sub-beams **410**, as described. Similarly, rear surface **223** of input coupler **220** may be configured to receive third portion of sub-beams **216** and provide a reflected third portion of sub-beams **416**, as described. Thus, reflected first portion of sub-beams **410**, second portion of sub-beams **212**, reflected third portion of sub-beams **416**, and fourth portion of sub-beams **218** may exit from input coupler bottom surface **227** at different angles, as described.

[0075] Optical device **602** may include a first waveguide **630** having a first diffraction grating **632** that may be configured to receive reflected first portion of sub-beams **410** and provide diffracted first portion of sub-beams **636**. First diffraction grating **632** may be configured to receive second portion of sub-beams **212** and provide diffracted second portion of sub-beams **638**. Together, diffracted first portion of sub-beams **636** and diffracted second portion of sub-beams **638** comprise a diffracted first portion of guided image beams **634** configured to advance by four-fold internal reflection along first waveguide **630** while rotating in opposite directions (e.g., in a helical manner). First diffraction grating **632** may be disposed adjacent to and co-planar with first waveguide top surface **635**, for example. First waveguide **630** may include a first aperture expander **640** configured to receive the diffracted first portion of guided image beams **634** and provide a first plurality of expanded image beams **648**.

[0076] First aperture expander **640** may be implemented as a second diffraction grating **646** configured to expand diffracted first portion of diffracted image beams **634** in a first dimension (e.g., expand laterally across a long axis **294** of first waveguide **630**) to provide a first plurality of expanded image beams **648** that may exit from first waveguide bottom surface **637**. Second diffraction grating **646** may be disposed adjacent to and co-planar with first waveguide bottom surface **637**. In this manner, first diffraction grating **632** and second diffraction grating **646** may be implemented as two diffractive elements having an opposing optical power to cancel chromatic dispersion. First waveguide **630** may be configured to receive the second portion of guided image beams **214** and provide a transmitted second portion of guided image beams **244**. First waveguide **630** may be similar in some ways to first waveguide **230** described in reference to FIGS. **2A-2B**.

[0077] A diffraction grating, such as first diffraction grating **632**, may be a passive optical element described generally as a diffractive optical element or a transmissive diffractive component having

a partially reflecting surface with a periodic structure (e.g., two-dimensional periodicity) that receives an incident light beam and provides a plurality of light beams at different angles where the diffraction grating may be embedded within a light-guide optical element **132** such as first waveguide **630**, for example. As used herein, a diffraction grating may be a refractive or reflective beam expander configured to receive an input beam on a first side and provide a plurality of output beams from a second side, where the output beams may be expanded in a first dimension (e.g., a lateral dimension) and may be used to receive and redirect light beams, similar to first mirror **232**, as described in reference to FIG. 2A, for example. Also, a diffractive optical element such as a diffraction grating may also be used as an aperture expander, similar to the plurality of parallel partially reflective facets **246** in first aperture expander **240**, as described in reference to FIG. 2A, and elsewhere.

[0078] Optical device **602** may include a second waveguide **650** having a third diffraction grating **652** that may be configured to receive reflected third portion of sub-beams **416** and provide diffracted third portion of sub-beams **656**. Third diffraction grating **652** may be configured to receive fourth portion of sub-beams **218** and provide diffracted fourth portion of sub-beams **658**. Together, diffracted second portion of sub-beams **656** and diffracted second portion of sub-beams **658** comprise a diffracted second portion of guided image beams **654** configured to advance by four-fold internal reflection along first waveguide **630** while rotating in opposite directions (e.g., in a helical manner). Third diffraction grating **652** may be disposed adjacent to and co-planar with second waveguide top surface **655**, for example. Second waveguide **650** may include a second aperture expander **660** positioned in a second region **662** that is laterally displaced **664** from first region **642** and configured to receive the diffracted second portion of guided image beams **654** and provide a second plurality of expanded image beams **668**.

[0079] Second aperture expander **660** may be implemented as a fourth diffraction grating **666** configured to expand diffracted second portion of diffracted image beams **654** in a first dimension (e.g., expand laterally across a long axis **294** of second waveguide **650**) to provide a second plurality of expanded image beams **668** that may exit from second waveguide bottom surface **657**. Fourth diffraction grating **666** may be disposed adjacent to and co-planar with second waveguide bottom surface **657**. In this manner, third diffraction grating **652** and fourth diffraction grating **666** may be implemented as two diffractive elements having an opposing optical power to cancel chromatic dispersion. Second waveguide **650** may be configured to receive first plurality of expanded image beams **648** and provide a transmitted first plurality of expanded image beams **678**. Second waveguide **650** may be similar in some ways to second waveguide **250** described in reference to FIGS. 2A-2B.

[0080] First aperture expander **640** and second aperture expander **660** may overlap laterally (e.g., horizontally as shown) by an overlap distance **690** that may range from between 1% to 20% of a length of first waveguide **630** and second waveguide **650**, which may be preferably equal in length. Overlap distance **690** may preferably range from between 5% to 10% of the length of first waveguide **630**. A technical benefit of first aperture expander **640** and second aperture expander **660** overlapping may promote continuity of the combined image, for example. Alternatively, first aperture expander **640** and second aperture expander **660** may not overlap, so the overlap distance **690** may be zero where image continuity is not an issue.

[0081] Optical device **602** may include a third waveguide **270** with a third aperture expander **272** (e.g., oriented vertically) positioned in a third region **274** and configured to receive the transmitted first plurality of expanded image beams **678** and the second plurality of expanded image beams **668** and provide a third plurality of expanded image beams **280** to exit a third waveguide rear surface **273** toward an eye box **282** and an eye **284** of a user or wearer of wearable device **110**. In this manner, third aperture expander **272** may be configured to expand transmitted first plurality of expanded image beams **678** and second plurality of expanded image beams **668** in a second dimension (e.g., expand vertically across a vertical axis **296** of third waveguide **270**) that is

orthogonal to the first dimension.

[0082] First waveguide **630** may include a first homogenizer **686** disposed in a parallel plane disposed vertically about midway between first waveguide top surface **635** and first waveguide bottom surface **637**, and disposed horizontally (e.g., laterally) between first diffraction grating **632** and first aperture expander **640**. In particular, first homogenizer **686** may be disposed horizontally in a position that may overlap a portion of either or both of first diffraction grating **632** and second diffraction grating **646**. Alternatively, first homogenizer **686** may not overlap any portion of either first diffraction grating **632** or second diffraction grating **646**. Similarly, second waveguide **650** may include a second homogenizer **688** disposed in a parallel plane disposed vertically about midway between second waveguide top surface **655** and second waveguide bottom surface **657**, and disposed horizontally (e.g., laterally) between third diffraction grating **652** and fourth expansion grating **666**. In particular, second homogenizer **688** may be disposed horizontally in a position that may overlap a portion of either or both of third diffraction grating **652** and fourth diffraction grating **666**. Alternatively, second homogenizer **688** may not overlap any portion of either third diffraction grating **652** or fourth diffraction grating **666**.

[0083] According to an example, optical device **602** may include a frame **148** (e.g., a structural element) configured to support wearable device **110**, two or more of controller **112**, memory **114**, power management module **116**, battery **118**, image projector **120**, light-guide **130** including two or more light-guide optical elements **132** such as first waveguide **630**, second waveguide **650**, third waveguide **270**, optical engine **142**, first waveguide **630**, second waveguide **650**, and third waveguide **270** in relative position to each other. In an example, frame **148** may support input coupler **220** and first waveguide **630** so that a first interface **213** between input coupler **220** and first waveguide **630** includes a first air gap. In an example, frame **148** may support first waveguide **630** and second waveguide **650** so that a second interface **215** between first waveguide **630** and second waveguide **650** includes a second air gap. In an example, frame **148** may support second waveguide **650** and third waveguide **270** so that a third interface **217** between second waveguide **650** and third waveguide **270** includes a third air gap. In an example, frame **148** may support first waveguide **630** and second waveguide **650** so that first waveguide **630** and second waveguide **650** may be fully concealed within frame **148**. As shown in FIG. **6A-6B**, first waveguide **630** may include diffractive elements and second waveguide **650** may include diffractive elements. Thus, optical device **602** and light-guide **130** may comprise a second stacked waveguide arrangement of a diffractive type.

[0084] FIG. **7A** illustrates a front plan view of an optical system including a light-guide, in accordance with various examples. FIG. **7B** illustrates a side plan view of an optical system including the light-guide of FIG. **7A**, in accordance with various examples. According to an example, optical device **702** may include a first input coupler **220A** configured to receive a first collimated image beam **206A** from a first image projector **120A** and to provide a first portion of guided image beams. Optical device **702** may include a second input coupler **220B** configured to receive a second collimated image beam **206B** from a second image projector **120B** and to provide the second portion of guided image beams.

[0085] As described in reference to FIG. **1** to FIG. **7B**, a first waveguide **730** may be configured to receive and expand in a first dimension **294** a first portion of guided image beams **208** based on a first image field **126A** and to provide a first plurality of expanded image beams **248**. A second waveguide **750** may be disposed adjacent to first waveguide **730** and configured to receive and expand in the first dimension one of a second portion of guided image beams **214** and a transmitted second portion of guided image beams **244** corresponding to a second image field **126D** that is different from the first image field and to provide a second plurality of expanded image beams **268**. Second waveguide **750** may be configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams **278**. Third waveguide **270** may be disposed adjacent to second waveguide **750** on a side opposite first waveguide **730**. Third

waveguide **270** may be configured to receive and expand in a second dimension **296** transmitted first plurality of expanded image beams **278** and second plurality of expanded image beams **268** to provide third plurality of expanded image beams **280**. First waveguide **730** may have a first aperture expander **740** positioned in a first region **742**. Second waveguide **750** may have a second aperture expander **760** positioned in a second region **762** that is laterally displaced **764** from first region **242**. First aperture expander **740** and second aperture expander **760** may overlap laterally (e.g., horizontally as shown) by an overlap distance **790** that may range from between, for example, 1% to 20% of a length of first waveguide **730** and second waveguide **750**, which may be preferably equal in length.

[0086] First input coupler **220A** may include a first input coupler rear surface **223A** having a reflective surface similar to reflective surface **408**. Similarly, second input coupler **220B** may include a second input coupler rear surface **223B** having a reflective surface similar to reflective surface **408**. First waveguide **230** may include a first homogenizer **786** disposed in a parallel plane disposed vertically about midway between first waveguide top surface **735** and first waveguide bottom surface **737**, and disposed horizontally (e.g., laterally) between a first mirror or a first diffraction grating and a first aperture expander. Similarly, second waveguide **750** may include a second homogenizer **788** disposed in a parallel plane disposed vertically about midway between second waveguide top surface **755** and second waveguide bottom surface **757**, and disposed horizontally (e.g., laterally) between a second mirror or a third diffraction grating and a second aperture expander. Various light homogenizers may be used, alone or in combination with each other, to provide improved illumination uniformity, among other benefits.

[0087] According to various examples disclosed herein, first waveguide **730** may include reflective elements and second waveguide **750** may include reflective elements so that optical device **702** and light-guide **130** may comprise a first stacked waveguide arrangement **761** of a reflective type, also illustrated in FIG. 2A-2B. Alternatively, first waveguide **730** may include diffractive elements and second waveguide **750** may include diffractive elements so that optical device **702** and light-guide **130** may comprise a second stacked waveguide arrangement **763** of a reflective type, also illustrated in FIG. 6A-6B. In another alternative, first waveguide **730** may include reflective elements and second waveguide **750** may include diffractive elements so that optical device **702** and light-guide **130** may comprise a third stacked waveguide arrangement **765** of a mixed reflective and diffractive type. In yet another alternative, first waveguide **730** may include diffractive elements and second waveguide **750** may include reflective elements so that optical device **702** and light-guide **130** may comprise a fourth stacked waveguide arrangement **767** of a mixed diffractive and reflective type.

[0088] As illustrated in FIG. 1-7B, optical device **702** may comprise a third stacked waveguide arrangement **765** which may include first waveguide **730** having a first mirror **232** configured to receive first portion of guided image beams **208** and provide a reflected first portion of guided image beams **234**. First waveguide **730** may include a first aperture expander **740** positioned in a first region **742**. First aperture expander **740** may include a first plurality of partially reflecting facets **246** disposed in first region **742**. First mirror **232** and first plurality of partially reflecting facets **246** may be parallel to each other and disposed at a first angle **239** relative to a long axis **294** of first waveguide **730**. First aperture expander **740** may be configured to receive reflected first portion of guided image beams **234** and provide a first plurality of expanded image beams **248**, where first waveguide **730** may be configured to receive second portion of guided image beams **214** and provide a transmitted second portion of guided image beams **244**. Optical device **702** may include second waveguide **750** that further a third diffraction grating **652** configured to receive transmitted second portion of guided image beams **244** and provide a diffracted second portion of guided image beams **654**. Second waveguide **750** may include a second aperture expander **760** positioned in a second region **762** that is laterally displaced **764** from first region **742**. Second aperture expander **760** may be configured to receive diffracted second portion of guided image

beams **654** and provide second plurality of expanded image beams **668**, wherein second waveguide **730** may be configured to receive first plurality of expanded image beams **648** and provide transmitted first plurality of expanded image beams **678**. Thus, first waveguide **730** may include reflective elements and second waveguide **750** may include diffractive elements so that optical device **702** and light-guide **130** may comprise a third stacked waveguide arrangement **765** having a mixed reflective and diffractive type.

[0089] Optical device **702** may comprise a fourth stacked waveguide arrangement **767** which may include first waveguide **730** having a first diffraction grating **632** configured to receive the first portion of guided image beams **208** and provide a diffracted first portion of guided image beams. First waveguide **730** may include a first aperture expander **740** positioned in a first region **742**. First aperture expander **740** may include a second diffraction grating **646** disposed in first region **742**. First aperture expander **740** may be configured to receive diffracted first portion of guided image beams **634** and provide first plurality of expanded image beams **648**, where first waveguide **730** is configured to receive second portion of guided image beams **214** and provide a transmitted second portion of guided image beams **244**. Second waveguide **750** may further include a second mirror **252** configured to receive the transmitted second portion of guided image beams **244** and provide a reflected second portion of guided image beams **254**. Second aperture expander **760** may be positioned in a second region **762** that is laterally displaced **764** from first region **742**. Second aperture expander **760** may be configured to receive the reflected second portion of guided image beams **254** and provide a second plurality of expanded image beams **268**, where second waveguide **750** is configured to receive first plurality of expanded image beams **248** and provide transmitted first plurality of expanded image beams **278**. Thus, first waveguide **730** may include diffractive elements and second waveguide **750** may include reflective elements so that optical device **702** and light-guide **130** may comprise a fourth stacked waveguide arrangement **767** having a mixed diffractive and reflective type.

[0090] According to an example, optical system **100** may include an optical device **702** comprising three waveguides that are each defined by at least two parallel front and back external faces, and where a collimated plurality of image beams may be guided within the three waveguides by total internal reflection. A first waveguide **730** may be configured to receive and expand in a first dimension a first portion of guided image beams based on a first image field and to provide a first plurality of expanded image guided beams in a section of first waveguide **730**, for example. A second waveguide **750** may be disposed adjacent to first waveguide **730**, where a section of second waveguide **750** may be configured to receive and expand in the first dimension a second portion of guided image beams based on a second image field that is different from the first image field and to provide a second plurality of expanded guided image beams. A same or a different section of second waveguide **750** may also be set to transmit the first plurality of expanded guided beams, for example. A third waveguide **270** may be disposed adjacent to second waveguide **750** on a side opposite first waveguide **730**, where third waveguide **270** may be configured to receive and expand in a second dimension the transmitted first plurality of expanded image guided beams and the second plurality of expanded image guided beams to provide a third plurality of expanded image beams which are unguided.

[0091] According to an example, at least one of the waveguides may provide a plurality of expanded image beams by using a set of mutually parallel embedded plane partial reflectors. Guided image beams may be coupled in to at least one of the waveguides by reflection from an embedded reflector (e.g., a partially or fully reflective mirror) that is parallel with the plurality of mutually parallel partial plane reflectors, for example. In this manner, reflection may be used for coupling in, expanding, and coupling out. Alternatively, at least one of the waveguides may provide a plurality of expanded image beams, where guided image beams may be coupled in by diffraction from a first diffracting element and then expanded by diffraction from a second diffracting element in the same waveguide prior to coupling out. In this manner, diffraction may be used for coupling

in, expanding, and coupling out.

[0092] A single image projector may be used to project collimated image beams onto a coupling-in arrangement of first waveguide **730** and second waveguide **750** where the coupling in arrangements may be offset from each other so that a first section of the field projects onto the first coupling arrangement and a second section of the field projects onto the second coupling arrangement. Alternatively, two image projectors may be used to project collimated image beams separately into the coupling in arrangements of each waveguide. At least one of first waveguide **730** and second waveguide **750** may include another pair of parallel external faces (e.g., top and bottom faces) that are perpendicular to the front and back faces, and that also reflect the image beams to propagate and advance by four-fold reflection along an optical path within the at least one waveguide. Thus, image beams may advance in a helical (e.g., a helix) or corkscrew-like manner. At least some of the plurality of expanded guided beams of first image portion from first waveguide may pass through the section in the second waveguide that provides expansion for the second image portion. Such overlap of image beams may provide for improved continuity. A homogenizer (e.g., a mixer), such as a partial reflector including partially reflective or fully reflective materials, may be incorporated within at least one of the waveguides, where the partial reflector may be parallel to one of the external faces of the at least one waveguide.

[0093] Various features in the various examples described separately above may be combined together unless they are incompatible with each other. For example, each of the features described in reference to FIG. **1** through FIG. **5** may be combined with the features described in reference to FIGS. **6A-6B** and FIGS. **7A-7B**, if such features are technically compatible.

[0094] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “includes”, “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. Also, terms such as top, bottom, above, adjacent, below, vertical, horizontal, lateral, side, fore, aft, and the like may describe relative placement of elements in a particular view illustrated in the drawings and should not be considered limiting. Such terminology may be applied oppositely when a view or element is inverted, for example.

[0095] The corresponding structures, materials, acts, and equivalents of all means or step plus function elements, if any, in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The various embodiments were chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.

Claims

1. An optical device comprising: a first waveguide configured to receive and expand in a first dimension a first portion of guided image beams based on a first image field and to provide a first plurality of expanded image beams; a second waveguide disposed adjacent to the first waveguide, the second waveguide configured to receive and expand in the first dimension one of a second portion of guided image beams and a transmitted second portion of guided image beams

corresponding to a second image field that is different from the first image field and to provide a second plurality of expanded image beams, the second waveguide configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams; and a third waveguide disposed adjacent to the second waveguide on a side opposite the first waveguide, the third waveguide configured to receive and expand in a second dimension the transmitted first plurality of expanded image beams and the second plurality of expanded image beams to provide a third plurality of expanded image beams.

2. The optical device of claim 1, wherein the first waveguide further comprises: a first mirror configured to receive the first portion of guided image beams and provide a reflected first portion of guided image beams; and a first aperture expander positioned in a first region, the first aperture expander configured to receive the reflected first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide is configured to receive the second portion of guided image beams and provide a transmitted second portion of guided image beams; and wherein the second waveguide further comprises: a second mirror configured to receive the transmitted second portion of guided image beams and provide a reflected second portion of guided image beams; and a second aperture expander positioned in a second region that is laterally displaced from the first region, the second aperture expander configured to receive the reflected second portion of guided image beams and provide a second plurality of expanded image beams, wherein the second waveguide is configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams.

3. The optical device of claim 2, wherein the first aperture expander comprises a first plurality of partially reflecting facets disposed in the first region, the first mirror and the first plurality of partially reflecting facets being parallel to each other and disposed at a first angle relative to a long axis of the first waveguide, and wherein the second aperture expander comprises a second plurality of partially reflecting facets disposed in the second region, the second mirror and the second plurality of partially reflecting facets being parallel to each other and disposed at a second angle relative to a long axis of the second waveguide, the second angle being different from the first angle.

4. The optical device of claim 3, wherein the reflected first portion of guided image beams are reflected within the first waveguide by total internal reflection between a first waveguide front surface and a first waveguide rear surface, and wherein the reflected second portion of guided image beams are reflected within the second waveguide by total internal reflection between a second waveguide front surface and a second waveguide rear surface.

5. The optical device of claim 1, wherein the first waveguide further comprises: a first diffraction grating configured to receive the first portion of guided image beams and provide a diffracted first portion of guided image beams; a first aperture expander positioned in a first region, the first aperture expander configured to receive the diffracted first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide is configured to receive the second portion of guided image beams and provide a transmitted second portion of guided image beams; and wherein the second waveguide further comprises: a third diffraction grating configured to receive the transmitted second portion of guided image beams and provide a diffracted second portion of guided image beams; a second aperture expander positioned in a second region that is laterally displaced from the first region, the second aperture expander configured to receive the diffracted second portion of guided image beams and provide a second plurality of expanded image beams, wherein the second waveguide is configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams.

6. The optical device of claim 5, wherein the first aperture expander includes a second diffraction grating configured to receive the diffracted first portion of guided image beams and provide the first plurality of expanded image beams, and wherein the second aperture expander includes a

fourth diffraction grating configured to receive the diffracted second portion of guided image beams and provide the second plurality of expanded image beams.

7. The optical device of claim 6, wherein the diffracted first portion of guided image beams are reflected within the first waveguide by total internal reflection between a first waveguide front surface and a first waveguide rear surface, and wherein the diffracted second portion of guided image beams are reflected within the second waveguide by total internal reflection between a second waveguide front surface and a second waveguide rear surface.

8. The optical device of claim 1, further comprising one of: a third stacked waveguide arrangement comprising: the first waveguide further comprises: a first mirror configured to receive the first portion of guided image beams and provide a reflected first portion of guided image beams; and a first aperture expander positioned in a first region, the first aperture expander including a first plurality of partially reflecting facets disposed in the first region, the first mirror and the first plurality of partially reflecting facets being parallel to each other and disposed at a first angle relative to a long axis of the first waveguide, the first aperture expander configured to receive the reflected first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide is configured to receive the second portion of guided image beams and provide a transmitted second portion of guided image beams; and the second waveguide further comprises: a third diffraction grating configured to receive the transmitted second portion of guided image beams and provide a diffracted second portion of guided image beams; and a second aperture expander positioned in a second region that is laterally displaced from the first region, the second aperture expander configured to receive the diffracted second portion of guided image beams and provide a second plurality of expanded image beams, wherein the second waveguide is configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams; and a fourth stacked waveguide arrangement comprising: the first waveguide further comprises: a first diffraction grating configured to receive the first portion of guided image beams and provide a diffracted first portion of guided image beams; and a first aperture expander positioned in a first region, the first aperture expander including a second diffraction grating disposed in the first region, the first aperture expander configured to receive the diffracted first portion of guided image beams and provide the first plurality of expanded image beams, wherein the first waveguide is configured to receive the second portion of guided image beams and provide a transmitted second portion of guided image beams; and the second waveguide further comprises: a second mirror configured to receive the transmitted second portion of guided image beams and provide a reflected second portion of guided image beams; and a second aperture expander positioned in a second region that is laterally displaced from the first region, the second aperture expander configured to receive the reflected second portion of guided image beams and provide a second plurality of expanded image beams, wherein the second waveguide is configured to receive the first plurality of expanded image beams and provide a transmitted first plurality of expanded image beams.

9. The optical device of claim 8, wherein one of the reflected first portion of guided image beams and the diffracted first portion of guided image beams are reflected within the first waveguide by total internal reflection between a first waveguide front surface and a first waveguide rear surface, and wherein one of the diffracted second portion of guided image beams and the reflected second portion of guided image beams are reflected within the second waveguide by total internal reflection between a second waveguide front surface and a second waveguide rear surface.

10. The optical device of claim 1, wherein the third waveguide further comprises: a third aperture expander positioned in a third region and configured to receive the transmitted first plurality of expanded image beams and the second plurality of expanded image beams and provide a third plurality of expanded image beams to exit a third waveguide rear surface.

11. The optical device of claim 10, wherein the third aperture expander comprises a third plurality of partially reflecting facets that are parallel to each other and are disposed at a third angle that is

oblique to a third waveguide front surface, and wherein the transmitted first plurality of expanded image beams and the second plurality of expanded image beams are reflected by total internal reflection between a third waveguide front surface and the third waveguide rear surface.

12. The optical device of claim 1, wherein the first dimension is orthogonal to the second dimension.

13. The optical device of claim 1, further comprising: an input coupler configured to receive a collimated image beam from an image projector and to provide the first portion of guided image beams and to provide the second portion of guided image beams, wherein the input coupler includes a reflective internal surface, the input coupler configured to receive the first portion of guided image beams having a first portion of sub-beams and a second portion of sub-beams, the input coupler configured to receive the second portion of guided image beams having a third portion of sub-beams and a fourth portion of sub-beams, the reflective internal surface configured to receive the first portion of sub-beams and provide a reflected first portion of sub-beams, the reflective internal surface configured to receive the third portion of sub-beams and provide a reflected third portion of sub-beams, wherein the first waveguide is configured to receive the reflected first portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a first direction, the first waveguide is configured to receive the second portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a second direction that is opposite the first direction, the reflected first portion of sub-beams and the second portion of sub-beams being expanded to provide the first plurality of expanded image beams, and wherein the second waveguide is configured to receive the reflected third portion of sub-beams configured to propagate in a four-fold helical manner along the second waveguide and rotate in a first direction, the second waveguide is configured to receive the fourth portion of sub-beams configured to propagate in a four-fold helical manner along the second waveguide and rotate in a second direction that is opposite the first direction, the reflected third portion of sub-beams and the fourth portion of sub-beams being expanded to provide the second plurality of expanded image beams.

14. The optical device of claim 13, further comprising: an image projector disposed adjacent to the input coupler and configured to provide a collimated image beam corresponding to an image field based on a digital image, the collimated image beam including the first portion of guided image beams corresponding to the first image field, the collimated image beam including the second portion of guided image beams corresponding to the second image field, wherein the collimated image beam is collimated to infinity.

15. The optical device of claim 1, further comprising: a first input coupler configured to receive a first collimated image beam from a first image projector and to provide the first portion of guided image beams; and a second input coupler configured to receive a second collimated image beam from a second image projector and to provide the second portion of guided image beams, wherein the first input coupler includes a first reflective internal surface, the first input coupler configured to receive the first portion of guided image beams having a first portion of sub-beams and a second portion of sub-beams, the first reflective internal surface configured to receive the first portion of sub-beams and provide a reflected first portion of sub-beams, wherein the first waveguide is configured to receive the reflected first portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a first direction, the first waveguide is configured to receive the second portion of sub-beams configured to propagate in a four-fold helical manner along the first waveguide and rotate in a second direction that is opposite the first direction, the reflected first portion of sub-beams and the second portion of sub-beams being expanded to provide the first plurality of expanded image beams, wherein the second input coupler includes a second reflective internal surface, the second input coupler configured to receive the second portion of guided image beams having a third portion of sub-beams and a fourth portion of sub-beams, the second reflective internal surface configured to receive the third portion of sub-

beams and provide a reflected third portion of sub-beams, and wherein the second waveguide is configured to receive the reflected third portion of sub-beams configured to propagate in a four-fold helical manner along the second waveguide and rotate in a first direction, the second waveguide is configured to receive the fourth portion of sub-beams configured to propagate in a four-fold helical manner along the second waveguide and rotate in a second direction that is opposite the first direction, the reflected third portion of sub-beams and the fourth portion of sub-beams being expanded to provide the second plurality of expanded image beams.

16. The optical device of claim 15, further comprising: a first image projector disposed adjacent to the first input coupler and configured to provide a first collimated image beam corresponding to the first image field based on at least a first portion of a digital image, the first collimated image beam including the first portion of guided image beams; and a second image projector disposed adjacent to the second input coupler and configured to provide a second collimated image beam corresponding to the second image field based on at least a second portion of the digital image, wherein the first collimated image beam and the second collimated image beam are collimated to infinity.

17. The optical device of claim 1, further comprising at least one of: a first homogenizer disposed in a plane between a first waveguide top surface and a first waveguide bottom surface, and a second homogenizer disposed in a plane between a second waveguide top surface and a second waveguide bottom surface.

18. The optical device of claim 1, further comprising at least one of: a first retarder waveplate disposed between a first waveguide bottom surface and a second waveguide top surface, the first retarder waveplate configured to receive at least one of the first plurality of expanded image beams and the transmitted second portion of guided image beams and to provide a first retarder output that is at least one of rotated and depolarized; and a second retarder waveplate disposed between a second waveguide bottom surface and a third waveguide top surface, the second retarder waveplate configured to receive at least one of the second plurality of expanded image beams and the transmitted first plurality of expanded image beams and to provide a second retarder output that is at least one of rotated and depolarized.

19. The optical device of claim 1, further comprising at least one of: a first dielectric coating disposed on an input coupler bottom surface; a second dielectric coating disposed on a first waveguide bottom surface; and a third dielectric coating disposed on a second waveguide bottom surface.

20. The optical device of claim 1, comprising at least one of: a frame configured to support the first waveguide, the second waveguide, and the third waveguide in relative position to each other, wherein the first waveguide and the second waveguide are fully concealed within the frame; a first interface between an input coupler and the first waveguide includes a first air gap; a second interface between the first waveguide and the second waveguide includes a second air gap; and a third interface between the second waveguide and the third waveguide includes a third air gap.
