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(54) **EMBEDDED IMAGE PIPE**

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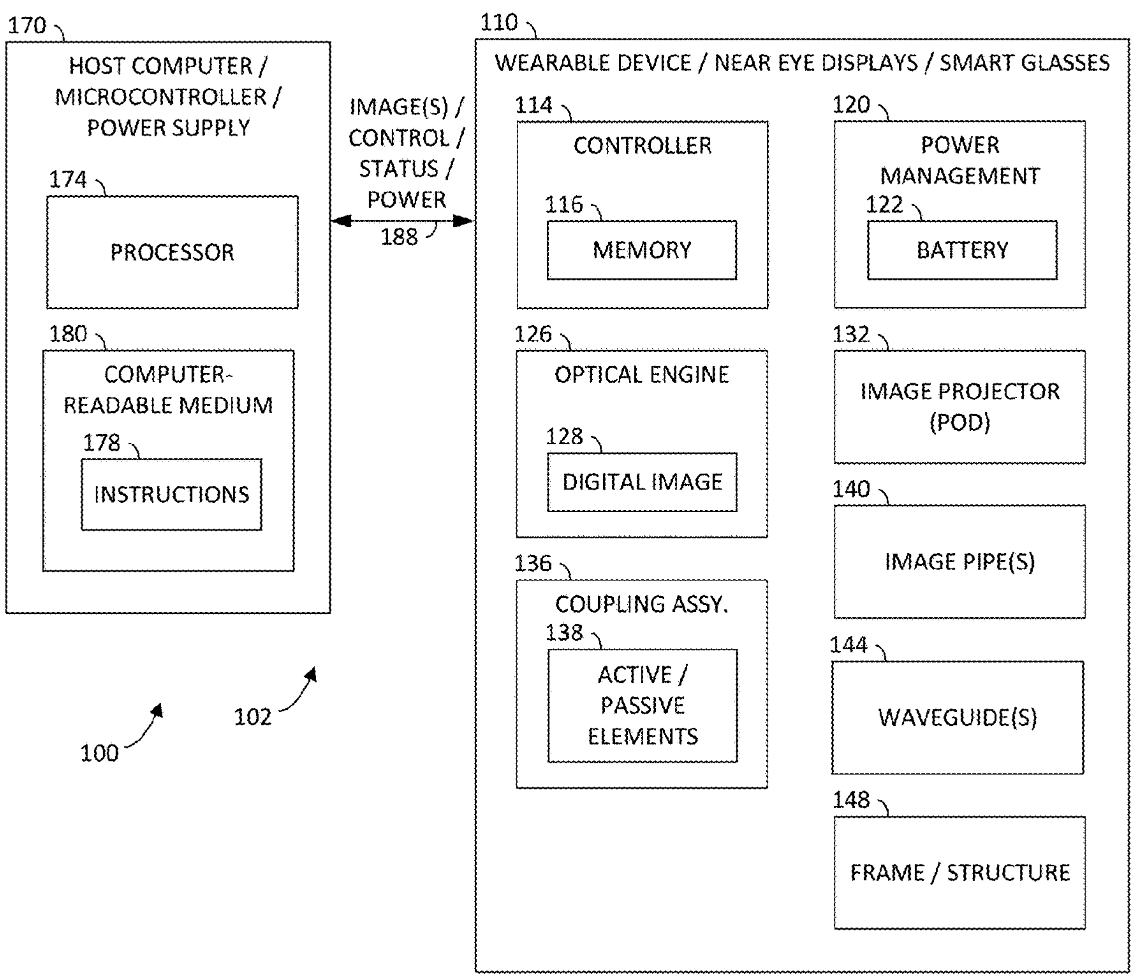
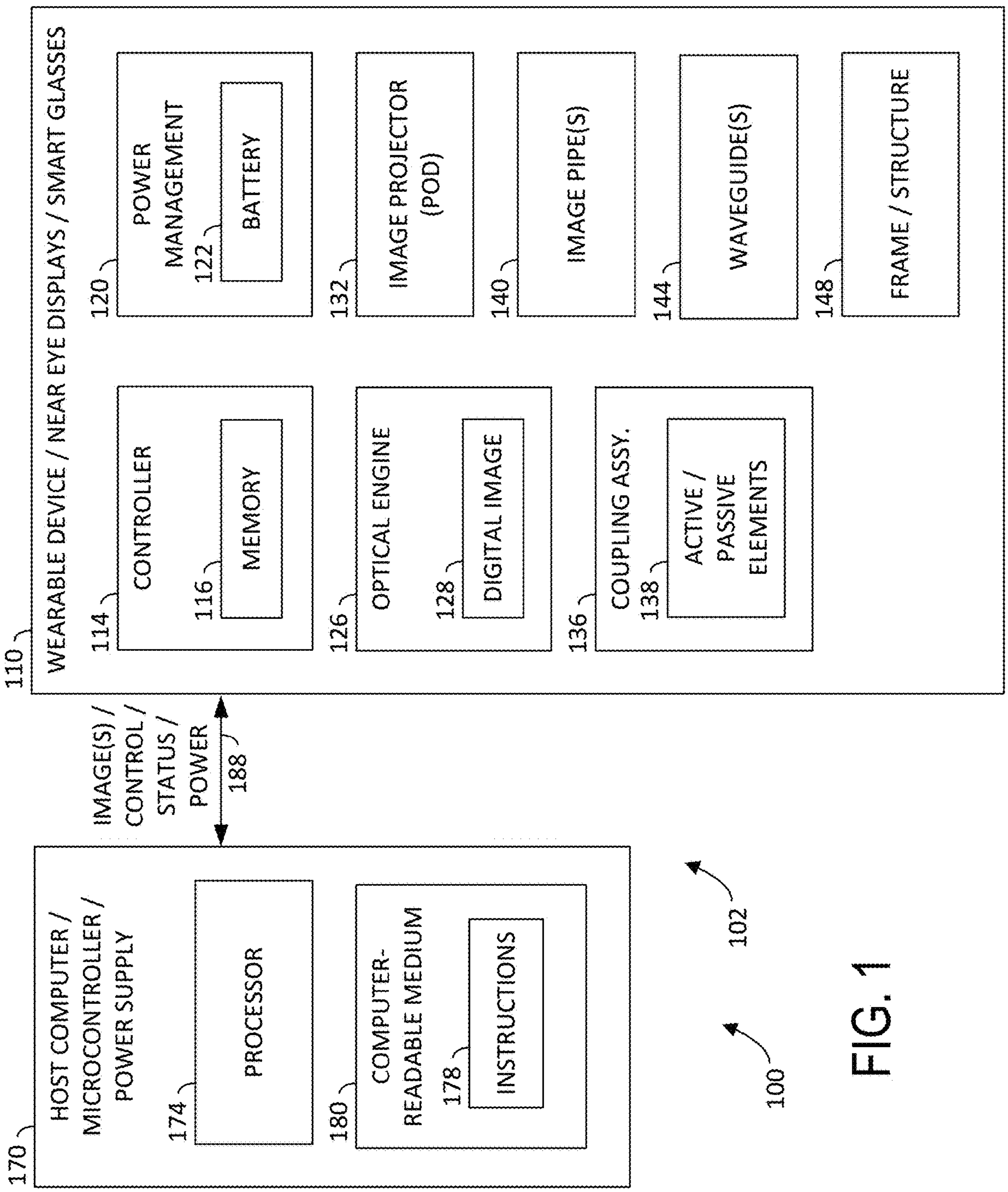
(57) **ABSTRACT**

An optical device may include a coupling assembly configured to receive a collimated image beam and provide a first output image beam and a second output image beam; an image pipe configured to receive the first output image beam at an image pipe input and provide at least one propagated image beam at an image pipe output; a first waveguide having a first waveguide rear surface, the first waveguide configured to receive the second output image beam and emit a first expanded output image beam from the first waveguide rear surface; and a second waveguide having a second waveguide rear surface, the second waveguide configured to receive the at least one propagated image beam and emit a second expanded output image beam from the second waveguide rear surface.

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WEARABLE DEVICE / NEAR EYE DISPLAYS / SMART GLASSES
114
CONTROLLER
116
MEMORY
120
POWER MANAGEMENT
122
BATTERY
126
OPTICAL ENGINE
128
DIGITAL IMAGE
132
IMAGE PROJECTOR (POD)
136
COUPLING ASSY.
138
ACTIVE / PASSIVE ELEMENTS
140
IMAGE PIPE(S)
144
WAVEGUIDE(S)
148
FRAME / STRUCTURE
IMAGE(S) / CONTROL / STATUS / POWER
188
170
HOST COMPUTER / MICROCONTROLLER / POWER SUPPLY
174
PROCESSOR
180
COMPUTER-READABLE MEDIUM
178
INSTRUCTIONS
102
100

FIG. 1

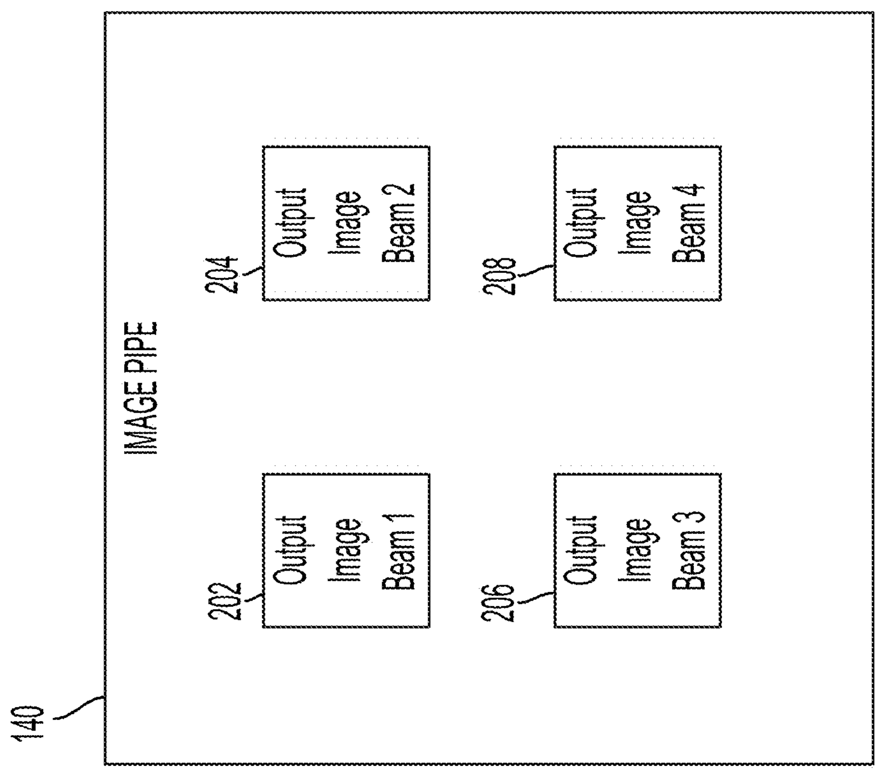
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IMAGE PIPE
202
Output Image Beam 1
204
Output Image Beam 2
206
Output Image Beam 3
208
Output Image Beam 4

FIG. 2

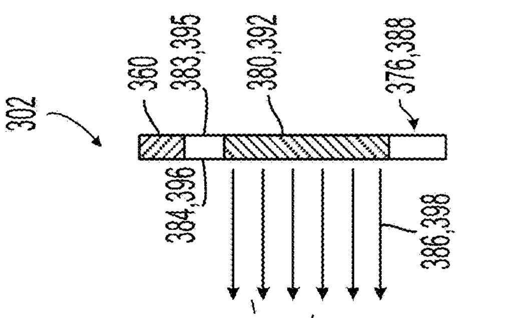


FIG. 3B

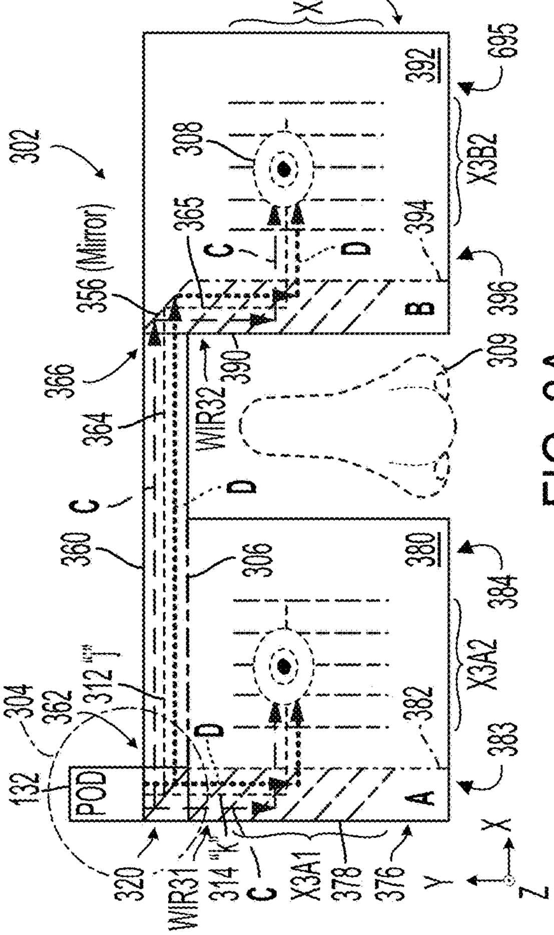


FIG. 3A

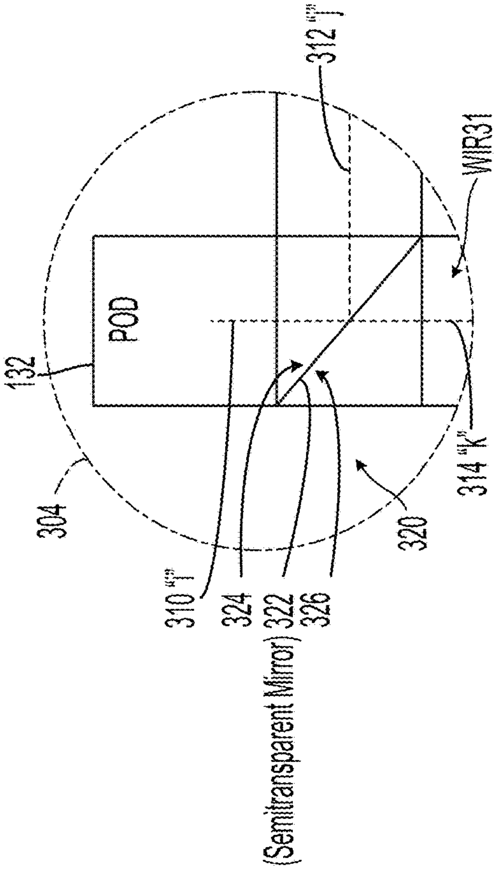
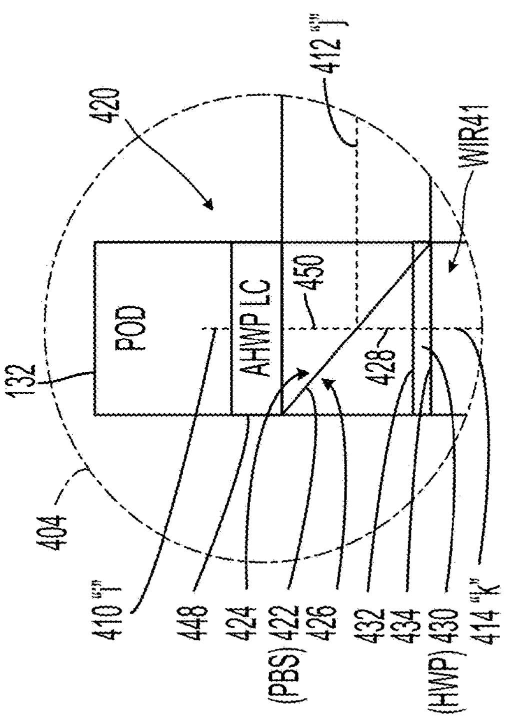


FIG. 3C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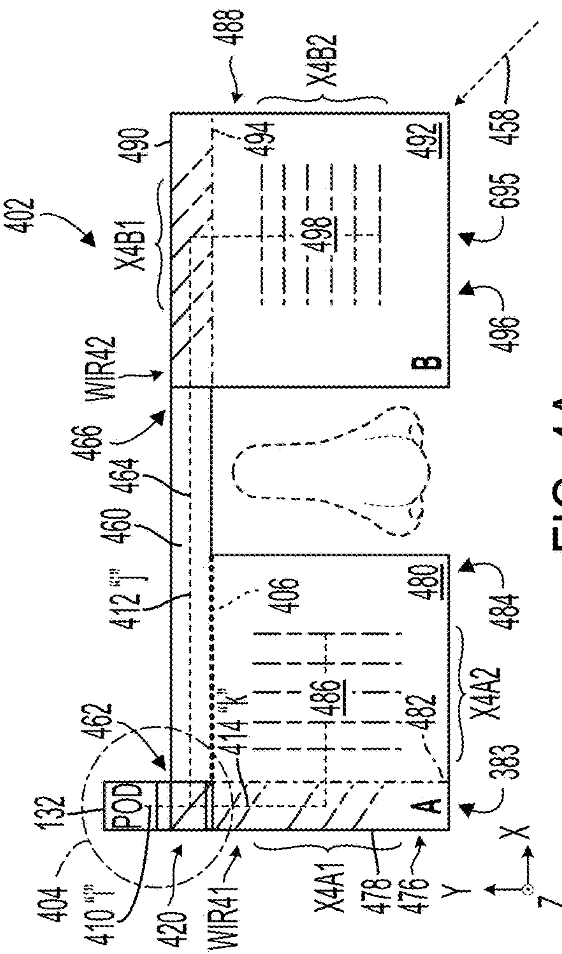
132
POD
AHWP LC
450
428
412 "J"
WIR41
404
410 "I"
448
424
(PBS) 422
426
432
434
(HWP) 430
414 "K"

FIG. 4B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494
X4B1
492
498
WIR42
466
464
460
412 "J"
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480
B
496
695
458
462
414 "K"
486
482
X4A2
484
383
A
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POD
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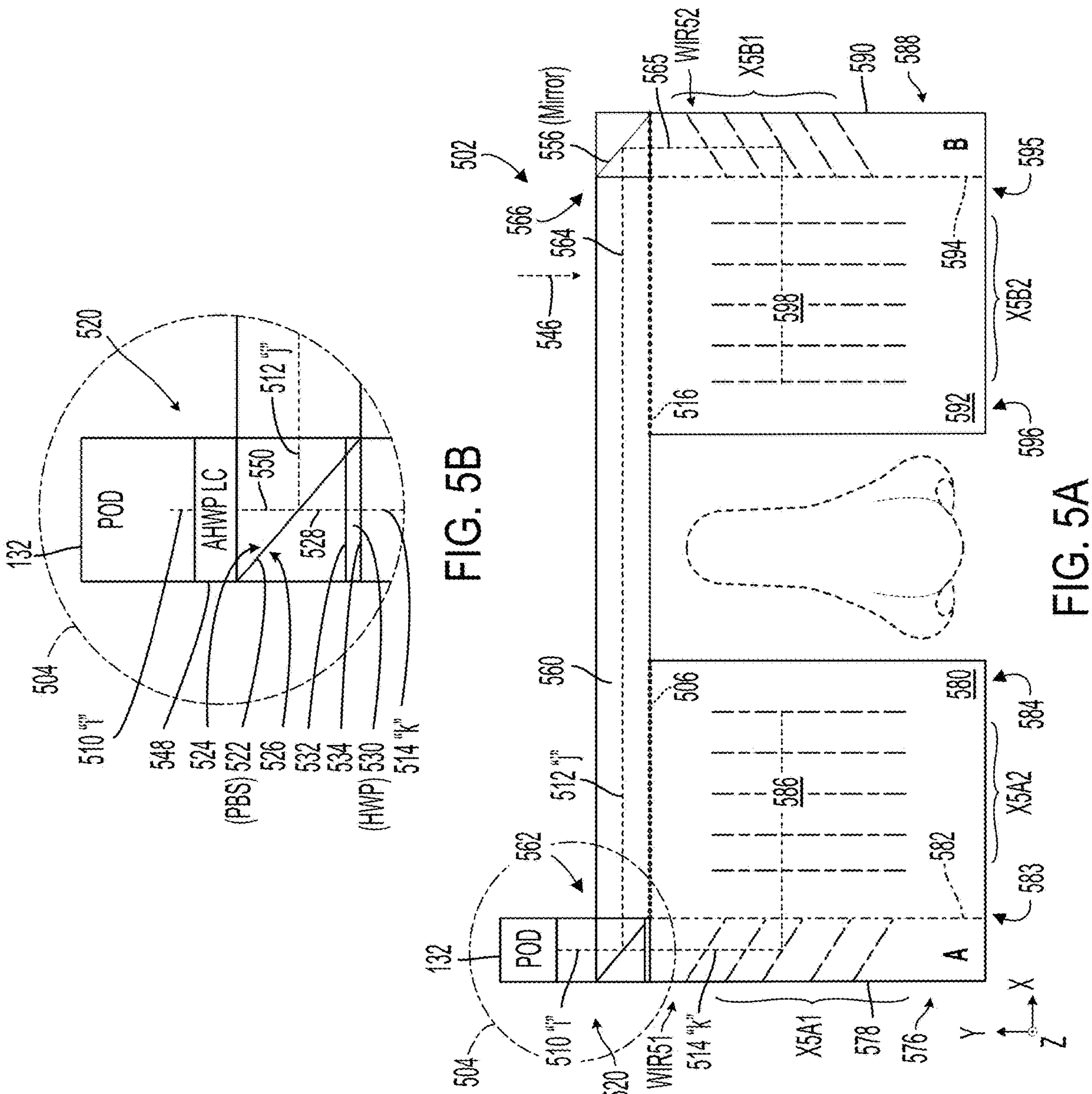
410 "I"
420
WIR41
X4A1
478
476
X
Y
Z

FIG. 4A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512 "J"
514 "K"
548
524
(PBS) 522
526
528
532
534
(HWP) 530
550
502
506
516
546
556 (Mirror)
560
562
564
565
566
576
578
580
582
583
584
586
588
590
592
594
595
596
598
WIR51
WIR52
X5A1
X5A2
X5B1
X5B2
A
B
X
Y
Z

FIG. 5B

FIG. 5A

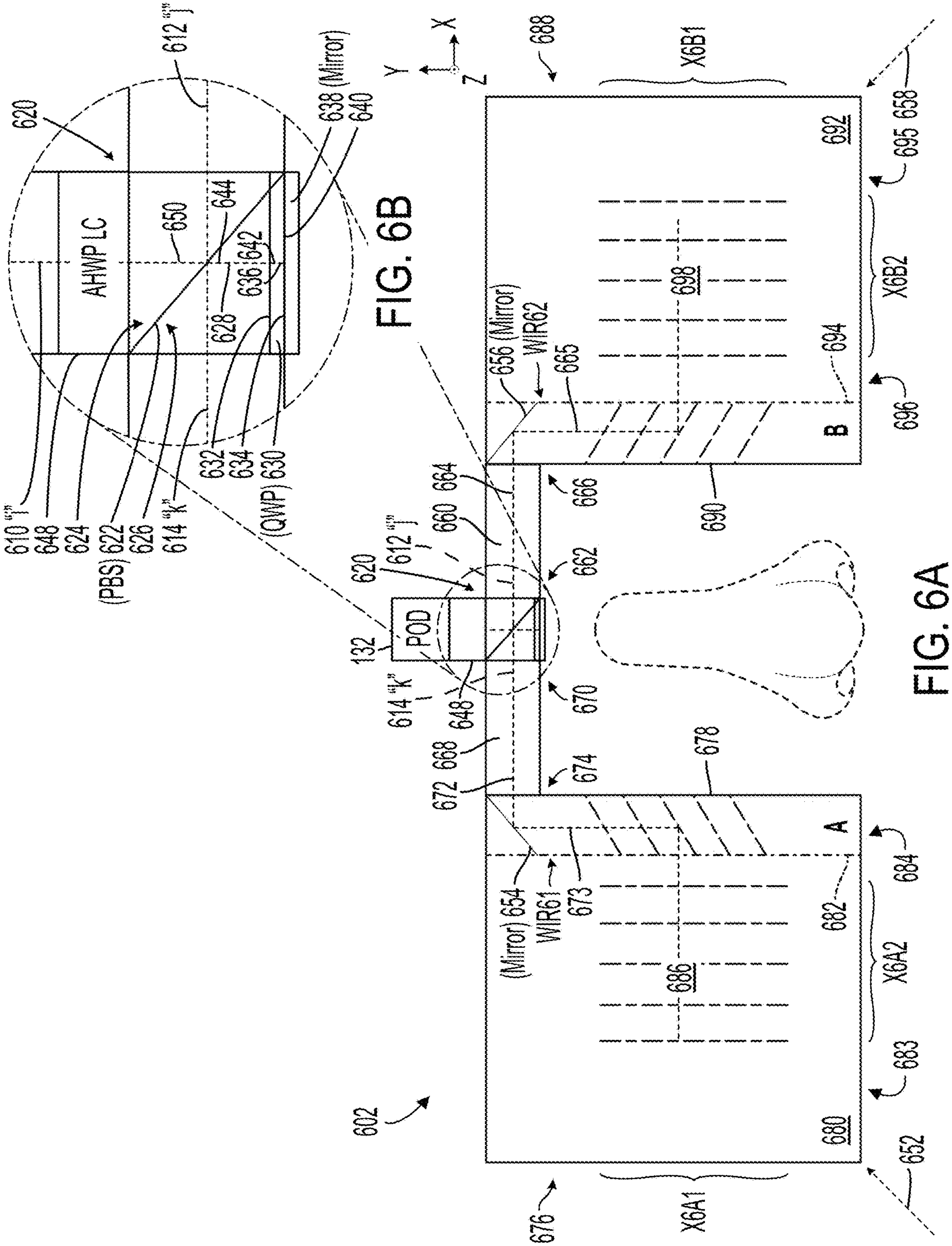

FIG. 6A

FIG. 6B

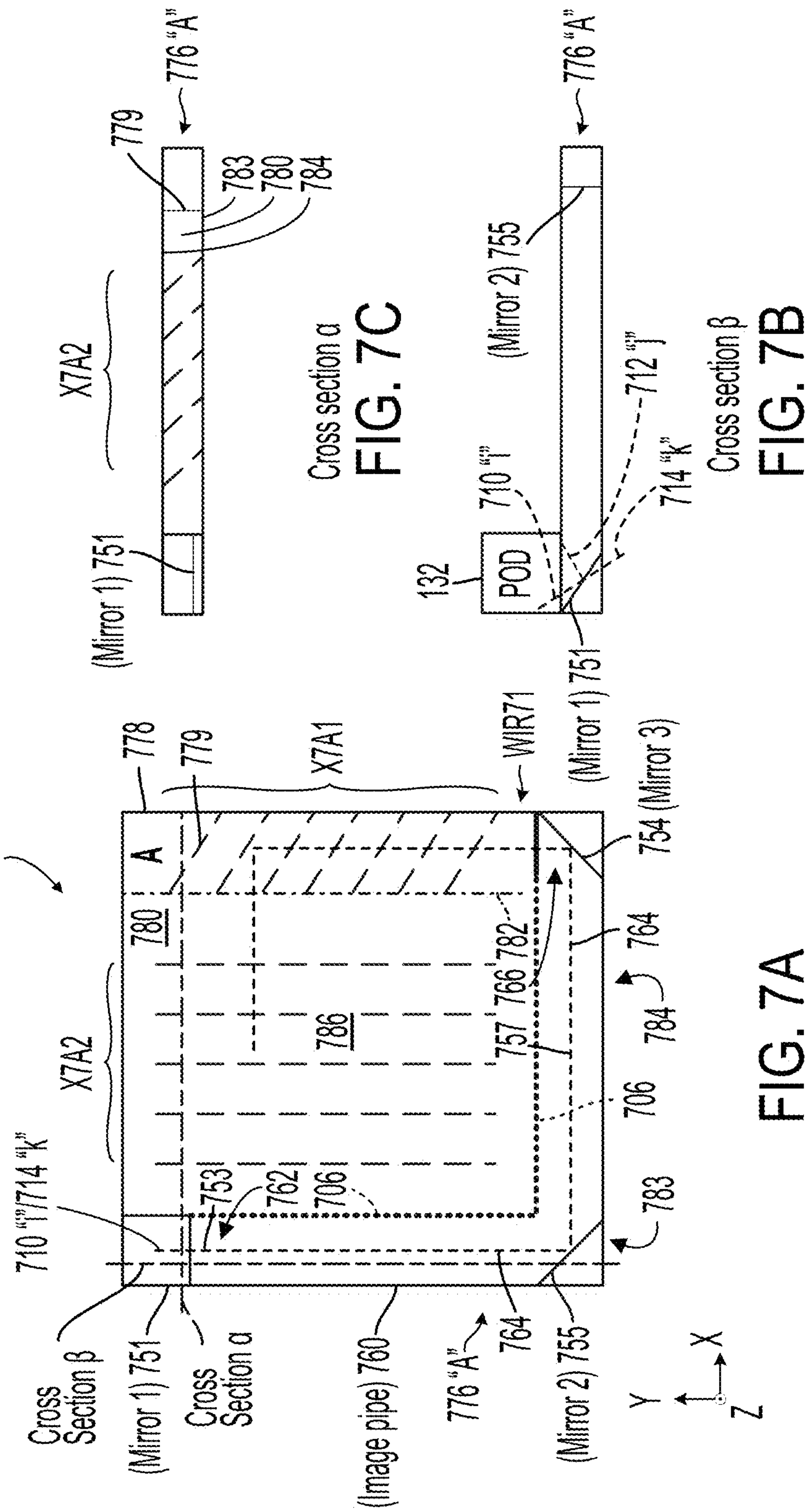

FIG. 7C

FIG. 7B

FIG. 7A

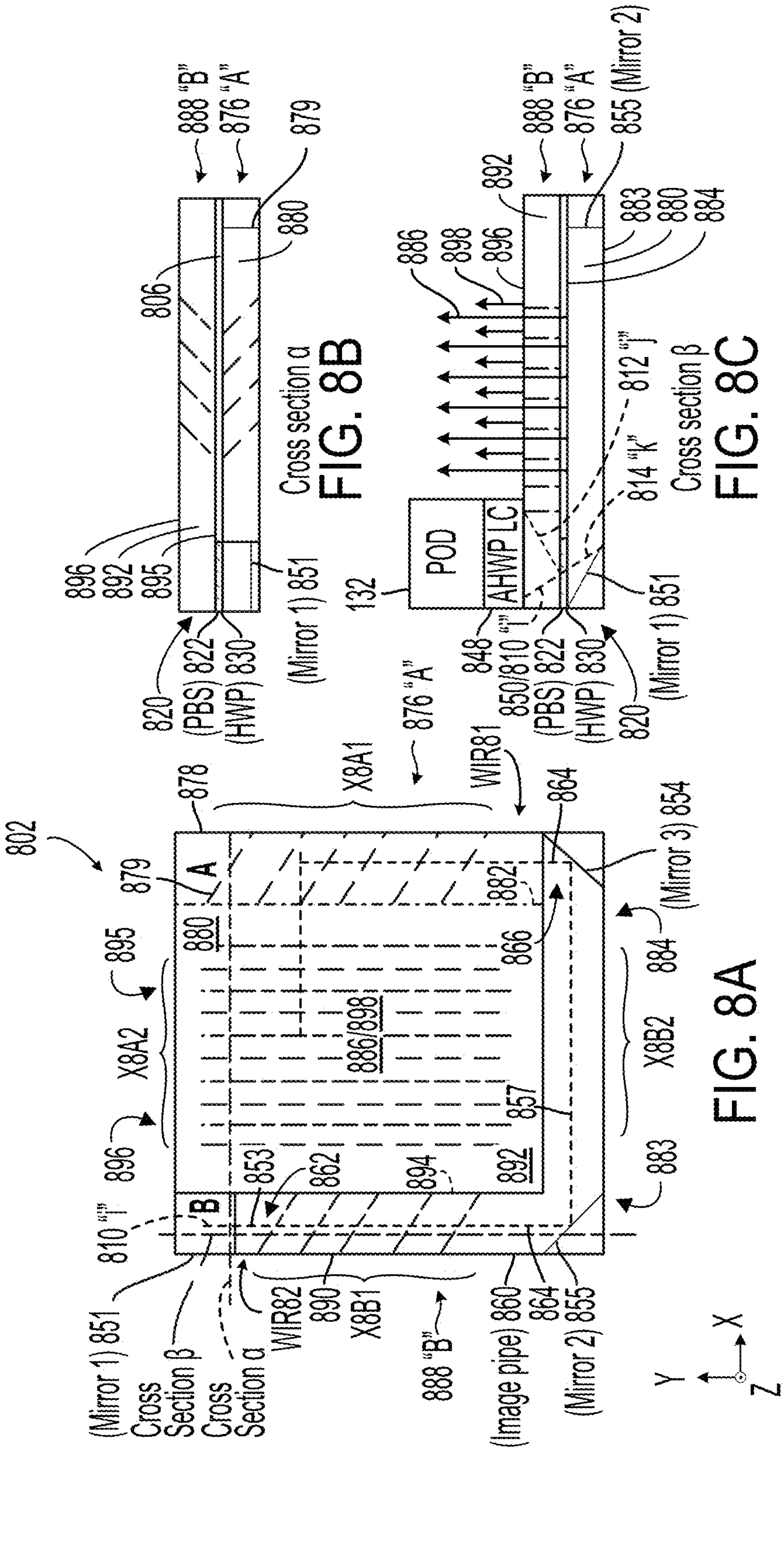

FIG. 8A

FIG. 8B

FIG. 8C

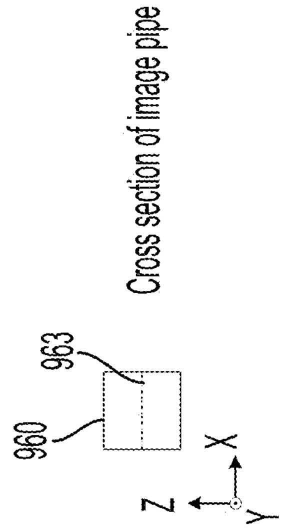

FIG. 9B

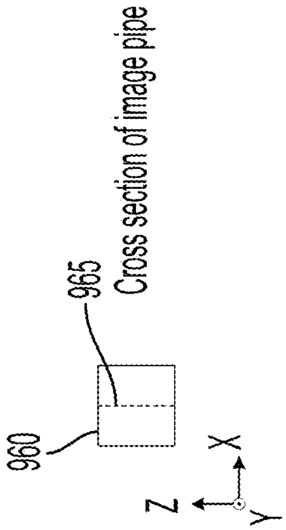

FIG. 9C

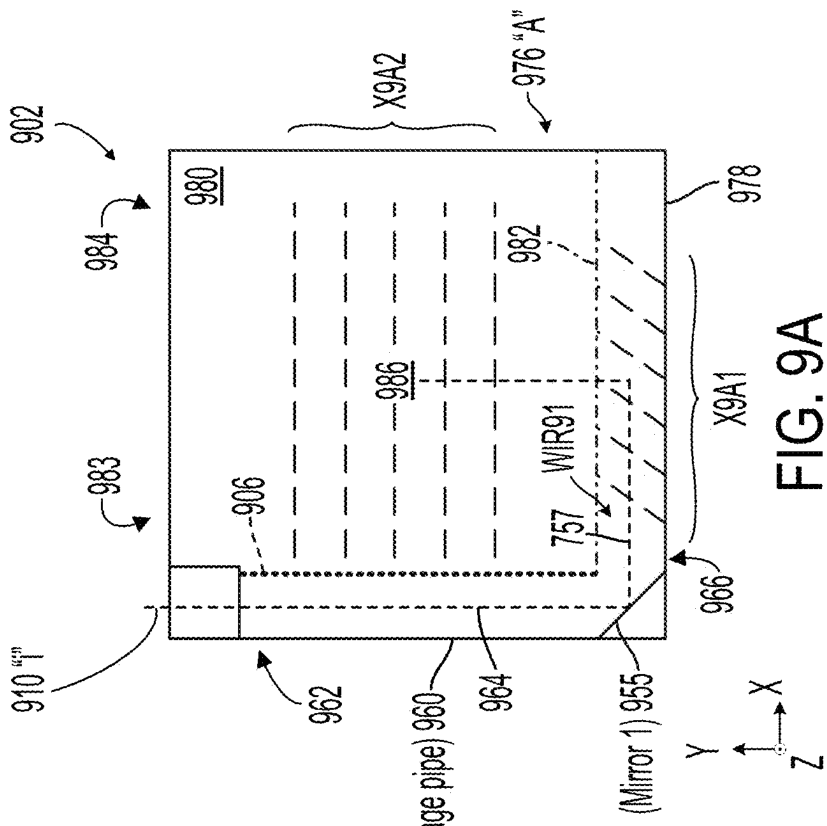

FIG. 9A

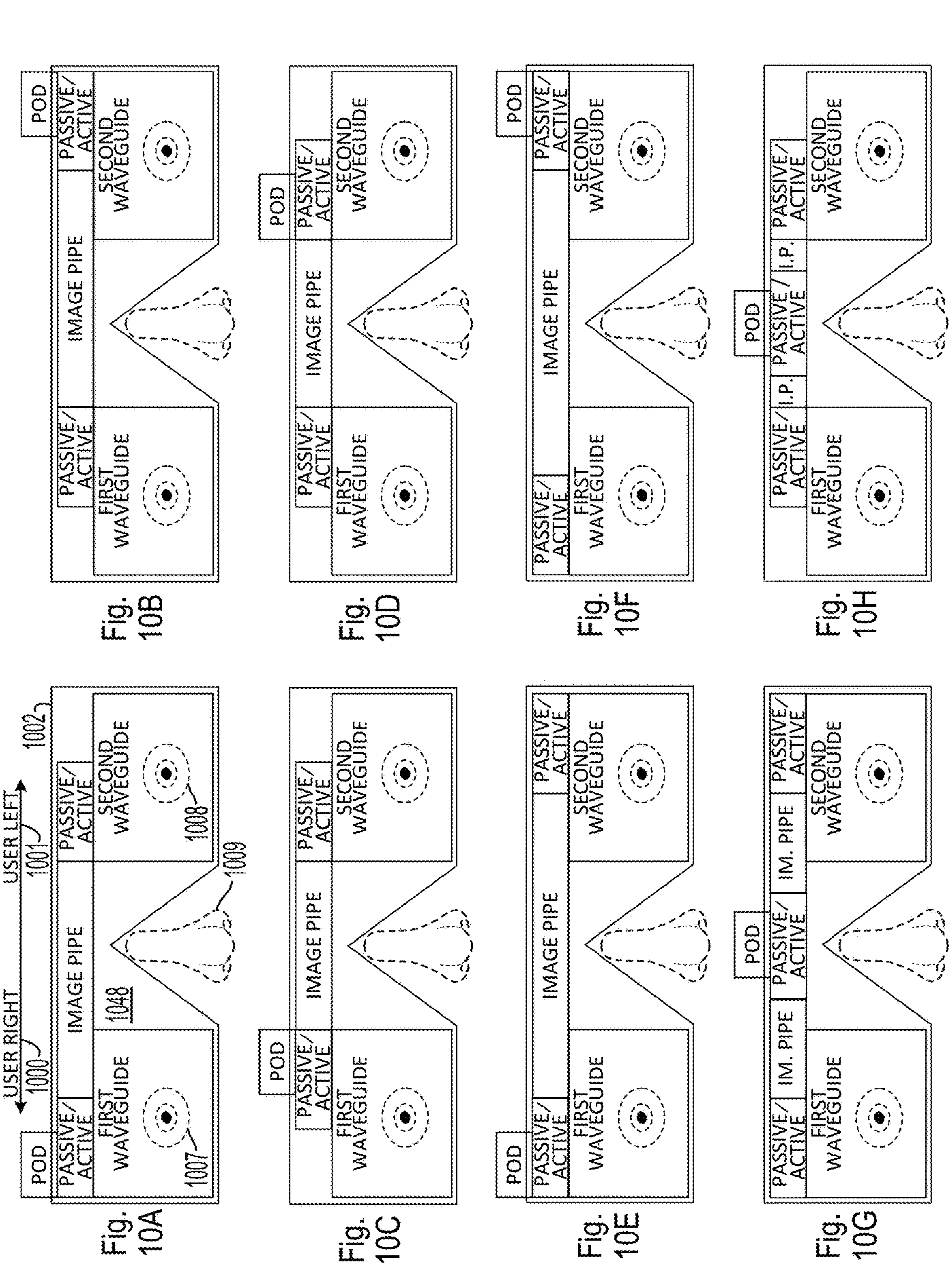

Fig. 10A

Fig. 10B

Fig. 10C

Fig. 10D

Fig. 10E

Fig. 10F

Fig. 10G

Fig. 10H

EMBEDDED IMAGE PIPE

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 Ser. No. 63/392,904 filed on Jul. 28, 2022, and titled Embedded Image Pipe, the entire 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 systems, devices, and methods of presenting optical information, more particularly, to head mounted displays (HMDs) and smart glasses (SGs) with near eye displays (NEDs) for presenting optical information to a user.

[0003] Conventional wearable optical devices, such as head mounted optical displays and smart glasses with near eye displays, are typically large and often are also heavy. Such devices may also suffer from a limited field of view (FoV) as well as performance limitations based on limited options for injecting images which sometimes may require large input apertures. This can limit the usability of such devices. Further, electronic components that drive these HMDs and SGs typically consume significant power leading to lower battery life, and yet still these devices may provide unclear augmented images, for example. What is needed are solutions that address these issues, and others.

SUMMARY

[0004] According to an example, an optical device is generally described. The optical device may include a coupling assembly configured to receive a collimated image beam and provide a first output image beam and a second output image beam; an image pipe configured to receive the first output image beam at an image pipe input and provide at least one propagated image beam at an image pipe output; a first waveguide having a first waveguide rear surface, the first waveguide configured to receive the second output image beam and emit a first expanded output image beam from the first waveguide rear surface; and a second waveguide having a second waveguide rear surface, the second waveguide configured to receive the at least one propagated image beam and emit a second expanded output image beam from the second waveguide rear surface.

[0005] According to this example, the optical device wherein the coupling assembly further comprises: a semitransparent mirror having a semitransparent mirror first surface and a semitransparent mirror second surface opposite the semitransparent mirror first surface, the semitransparent mirror first surface configured to receive the collimated image beam and provide the first output image beam reflected from the semitransparent mirror first surface and provide the second output image beam emitted from the semitransparent mirror second surface. The optical device wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; wherein the second waveguide comprises a mirror configured to receive the at least one propagated image beam and provide a reflected at least one propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam. The optical device may further include an image projector configured to provide the collimated image beam based on a digital image, wherein the collimated image beam is collimated to infinity, and wherein the projector includes a liquid crystal on silicon display.

[0006] According to another example, an optical system is generally described. An optical system may include an image projector configured to provide a collimated image beam based on a digital image; a coupling assembly configured to receive the collimated image beam and provide a first output image beam and a second output image beam; an image pipe configured to receive the first output image beam at an image pipe input and provide at least one propagated image beam at an image pipe output; a first waveguide having a first waveguide rear surface, the first waveguide configured to receive the second output image beam and emit a first expanded output image beam from the first waveguide rear surface; and a second waveguide having a second waveguide rear surface, the second waveguide configured to receive the at least one propagated image beam and emit a second expanded output image beam from the second waveguide rear surface.

[0007] According to this example, the optical system wherein at least one of: the collimated image beam is collimated to infinity; the projector includes one of a liquid crystal display, a liquid crystal on silicon display, an organic light emitting diode display, a micro light emitting diode display, and a laser display; the image pipe includes at least one of a glass material, an acrylic material, and a polycarbonate material; a portion of the first waveguide is affixed to a portion of the image pipe with a layer of low refractive index adhesive; and the image pipe is an elongated transparent member having a first end and a second end with a rectangular cross section and orthogonal walls, the image pipe configured to receive at least one input image beam and provide four replicated output image beams based on the at least one input image beam. The optical system wherein the coupling assembly comprises a semitransparent mirror having a semitransparent mirror first surface and a semitransparent mirror second surface opposite the semitransparent mirror first surface, the semitransparent mirror first surface configured to receive the collimated image beam and provide the first output image beam reflected from the semitransparent mirror first surface and to provide the second output image beam emitted from the semitransparent mirror

second surface; and wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; wherein the second waveguide comprises a mirror configured to receive the at least one propagated image beam and provide a reflected at least one propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

[0008] According to this example, the optical system wherein the coupling assembly comprises: a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the collimated image beam and provide the first output image beam from the polarizing beam splitter first side and provide a transmitted image beam from the polarizing beam splitter second side; and a half wave plate having a half wave plate first side and a half wave plate second side, the half wave plate being configured to receive the transmitted image beam at the half wave plate first side and provide the second output image beam from the half wave plate second side. The optical system wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and wherein the second waveguide comprises a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

[0009] According to this example, the optical system wherein the coupling assembly further comprises: an active half wave plate liquid crystal element configured to receive the collimated image beam and provide a transformed image beam; a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the transformed image beam and provide the first output image beam from the polarizing beam splitter first side and provide a transmitted image beam from the polarizing beam splitter second side; and a half wave plate having a half wave plate first side and a half wave plate second side, the half wave plate being configured to receive the transmitted image beam on the half wave plate first side and provide the second output image beam from the half wave plate second side. The optical system wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; wherein the second waveguide comprises a mirror configured to receive the at least one propagated image beam and provide a reflected at least one propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

[0010] According to this example, the optical system wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and wherein the second waveguide comprises a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam. The optical system wherein the image pipe is a first image pipe and wherein the first waveguide includes a first waveguide front surface that is opposite the first waveguide rear surface, the optical system further comprising: a third waveguide having a third waveguide rear surface, the third waveguide configured to receive the second output image beam and emit a third expanded output image beam from the third waveguide rear surface, the third waveguide rear surface being affixed to the first waveguide front surface, the third waveguide comprising: a second image pipe configured to receive the second output image beam and provide at least one propagated third image beam at a third image pipe output; a third waveguide first aperture expander, the third waveguide first aperture expander configured to expand the at least one propagated third image beam and provide a third waveguide first plurality of expanded image beams; and a third waveguide second aperture expander configured to expand the first plurality of expanded image beams and provide a third waveguide second plurality of expanded image beams to be emitted as the third expanded output image beam, the second image pipe configured to surround at least a portion of the third waveguide second aperture expander. The optical system further comprising: a frame configured to support the image projector, the coupling assembly, the image pipe, the first waveguide and the second waveguide, the frame being configured to conceal the image pipe within a portion of the frame.

[0011] According to yet another example, an optical system may include an image projector configured to provide a collimated image beam based on a digital image; a coupling assembly configured to receive the collimated image beam and provide a first output image beam and a second output image beam; a first image pipe configured to receive the first output image beam at a first image pipe input and provide an at least one first propagated image beam at a first image pipe output; a second image pipe configured to receive the second output image beam at a second image pipe input and provide an at least one second propagated image beam at a second image pipe output; a first waveguide having a first waveguide rear surface, the first waveguide configured to receive the at least one second propagated image beam and emit a first expanded output image beam from the first waveguide rear surface; and a second waveguide having a second waveguide rear surface, the second waveguide configured to receive the at least one first propagated image beam and emit a second expanded output image beam from the second waveguide rear surface.

[0012] According to this example, the optical system wherein the coupling assembly comprises: an active half wave plate liquid crystal element configured to receive the collimated image beam and provide a transformed image beam; a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the transformed image beam and provide the second output image beam from the polarizing beam splitter first side and provide a transmitted image beam from the polarizing beam splitter second side; a quarter wave plate having a quarter wave plate first side and a quarter wave plate second side, the quarter wave plate being configured to receive the transmitted image beam on the quarter wave plate first side and provide a converted image beam from the quarter wave plate second side; and a mirror having a reflective mirror surface configured to receive the converted image beam and provide a reflected image beam, the quarter wave plate configured to receive the reflected image beam on the quarter wave plate second side and provide a second converted image beam from the quarter wave plate first side, the polarizing beam splitter configured to receive the second converted image beam on the polarizing beam splitter second side and provide the first output image beam.

[0013] According to this example, the optical system wherein the first waveguide comprises a first mirror configured to receive the at least one second propagated image beam and provide a reflected at least one second propagated image beam, the first waveguide further comprising a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the reflected at least one second propagated image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; wherein the second waveguide comprises a second mirror configured to receive the at least one first propagated image beam and provide a reflected at least one first propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one first propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam. The optical system wherein the first waveguide includes a first waveguide front surface that is opposite the first waveguide rear surface, the optical system further comprising: a third waveguide having a third waveguide rear surface, the third waveguide configured to receive the at least one second propagated image beam and emit a third expanded output image beam from the third waveguide rear surface, the third waveguide rear surface being affixed to the first waveguide front surface, the third waveguide comprising: a third image pipe configured receive the at least one second propagated image beam and provide an at least one propagated third image beam at a third image pipe output; a third waveguide first aperture expander, the third waveguide first aperture expander configured to expand the at least one propagated third image beam and provide a third waveguide first plurality of expanded image beams; and a third waveguide second aperture expander configured to expand the first plurality of expanded image beams and provide a third waveguide second plurality of expanded image beams to be emitted as the third expanded output image beam, the second image pipe configured to surround at least a portion of the third waveguide second aperture expander, the second image pipe having a homogenizing layer.

[0014] According to this example, the optical system wherein the second waveguide includes a second waveguide front surface that is opposite the second waveguide rear surface, the optical system further comprising: a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the at least one first propagated image beam and provide a second transmitted image beam from the polarizing beam splitter second side; a half wave plate having a half wave plate first side and a half wave plate second side, the half wave plate being configured to receive the second transmitted image beam on the half wave plate first side and provide a second converted image beam from the half wave plate second side; a fourth waveguide having a fourth waveguide rear surface, the fourth waveguide configured to receive the second converted image beam and emit a fourth expanded output image beam from the fourth waveguide rear surface, the fourth waveguide rear surface being affixed to the second waveguide front surface, the fourth waveguide comprising: a fourth image pipe configured to receive the second converted image beam and provide an at least one propagated fourth image beam at a fourth image pipe output; a fourth waveguide first aperture expander, the fourth waveguide first aperture expander configured to expand the at least one propagated first image beam and provide a fourth waveguide first plurality of expanded image beams; and a fourth waveguide second aperture expander configured to expand the fourth plurality of expanded image beams and provide a fourth waveguide second plurality of expanded image beams to be emitted as the fourth expanded output image beam, the fourth image pipe configured to surround at least a portion of the fourth waveguide second aperture expander, the fourth image pipe including a homogenizing layer. The optical system further comprising: a frame configured to support the image projector, the coupling assembly, the first image pipe, the second image pipe, the first waveguide and the second waveguide, the frame being configured to conceal the first image pipe and the second image pipe within a portion of the frame.

[0015] The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description. In the drawings and the description, like reference numbers and/or like element names may indicate identical or functionally similar elements.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. **1** illustrates a block diagram of an optical system, in accordance with various examples of the present disclosure.

[0017] FIG. **2** illustrates an end view of an image pipe, in accordance with various examples of the present disclosure.

[0018] FIGS. **3**A-**3**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure.

[0019] FIGS. **4**A-**4**B illustrate details regarding an optical system, in accordance with various examples of the present disclosure.

[0020] FIGS. **5**A-**5**B illustrate details regarding an optical system, in accordance with various examples of the present disclosure.

[0021] FIGS. **6**A-**6**B illustrate details regarding an optical system, in accordance with various examples of the present disclosure.

[0022] FIGS. **7**A-**7**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure.

[0023] FIGS. **8**A-**8**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure.

[0024] FIGS. **9**A-**9**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure.

[0025] FIGS. **10**A-**10**H illustrate details regarding various configurations of optical systems, in accordance with various examples of the present disclosure.

DETAILED DESCRIPTION

[0026] 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.

[0027] 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. The system can efficiently provide high quality optical information to a user in various applications.

[0028] 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 configured separately or together as smart glasses, which may be worn on or about the head of a user to convey optical information to one or more eyes of a user.

[0029] Wearable device **110** may include a controller **114** with a memory **116** where controller **114** may be configured to send and receive electrical signals to various other elements in optical system **100**, to execute program instructions stored in memory **116** 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 **114** may include a microcontroller, a processor, various discrete components, programmable logic devices, and/or various interface circuits that may access memory **116** which may be removable, replaceable, programmable, and reprogrammable to update instructions to controller **114**.

[0030] Wearable device **110** may also include a power management module **120** having a battery **122** configured to provide power, where power management module **120** may be configured to charge, discharge, and monitor power usage for battery **122**. Various elements of wearable device **110** may receive power and/or control signals, including controller **114**, an image projector **132**, an optical engine **126**, and various active element **138** in one or more coupling assemblies **136**, for example. Various coupling assemblies **136** may include one or more cube beam splitters, semi-transparent mirrors, polarizing beam splitters, a half wave plates (e.g., half-wavelength retardation plates), quarter wave plates (e.g., to convert linearly polarized light into circularly polarized light and vice versa), and the like.

Various active elements **138** may include electronically controllable active half wave plate liquid crystal (AHWP LC) elements, and the like.

[0031] Image projector(s) **126**, may also described as a compact image projector, a micro-display projector, or a projecting optical device (POD), may be configured to produce a collimated image beam based on a digital image **128**. The collimated image beam may be collimated to infinity. The collimated image beam may be generated by various projecting optical devices, including a spatial light modulator (SLM) providing a two-dimensional (2D) array of pixel elements, each of the pixel elements being controllable to modulate a property, typically polarization, of light transmitted or reflected by the pixel element. An example of a transmitted light SLM is a liquid crystal display (LCD), while an example of a reflective SLM is a liquid crystal on silicon (LCOS) device or a digital light processing (DLP) device. Image projector **126** may include a liquid crystal display (LCD), a liquid crystal on silicon (LCoS) display, an organic light emitting diode (OLED) display, a micro light emitting diode (Micro-LED) display, and a laser display (LD), or the like. The representations described herein illustrate emission and progression of an image beam along an optical path, but it will be appreciated that this optical path can be folded, reflected, split, and further modulated by various active or passive elements, as described below. In this manner, the collimated image beam may be an illuminated representation of the digital image having an image field which is a two-dimensional representation of the digital image based on either a single graphical image (e.g., a static image) or a sequence of graphical images (e.g., a moving image) corresponding to different points within an image field that may be propagated through various optical elements in optical system **100**. The term beam may also be used to refer to a ray, such as an image ray, herein. Commonly, a beam may refer to a coherent ray that may be emitted from a coherent source, such as a LASER, for example. As used herein, the terms ray and beam may be used almost synonymously in some circumstances.

[0032] Wearable device **110** may also include one or more waveguides **144** such as light-guide optical elements **144** (e.g., LOEs) comprising transparent materials configured to receive, propagate, and emit illumination related to the digital image in proximity to an eye of a user for the purpose of communicating information. For example, the transparent material comprising waveguide **144** may include optical glass or other suitable material that may be transformed into complex or compound optical structures using a process that may include coating, stacking, slicing, polishing, assembling, and shaping the transparent materials. The process may include the addition of partially reflective or fully reflective materials such as mirror coatings, and/or low index of reflection (LRI) adhesives or glues to assemble various elements together, for example. By preparing and assembling elements using low index of reflection adhesives, various elements may be fabricated and tested separately prior to assembly, which may reduce cost.

[0033] Optical engine **126** may be operably coupled to image projector **132** in order to provide power and control signals and to receive status signals, for example. Optical engine **126** may be configured to operate image projector **132** under the direction of the controller **114**. For example, optical engine **126** may perform graphics processing for modifying digital image **128** before projection of an illuminated representation of the digital image by image projector **132**. Image projector **132** may be coupled with the one or more waveguides **144** by one or more coupling assemblies **136** having one or more active and/or passive elements **138**. Coupling assembly **136** may include one or more active elements such as an active half wave plate liquid crystal (AHWP LC) element, an active half wave plate, or a spatial light modulator (SLM), for example. Coupling assembly **136** may also include one or more passive elements such as one or more fully reflective mirrors, one or more partially reflective (e.g., semitransparent) mirrors, one or more half wave plates, one or more quarter wave plates, and various optical coatings which may be disposed between or upon various optical elements.

[0034] Wearable device **110** may also include a frame **148** (e.g., a head-mounted structure) for supporting and retaining one or more elements in wearable device **110**. For example, frame **148** may directly or indirectly support and retain image projector **126** in a position next one or more image pipes **140** and one or more waveguides **144**. In this manner, frame **148** may support and retain an optical engine **126**, an image projector **132** and one or waveguides **144** on or about the head of a user, for example. 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 may be described in various drawing figures.

[0035] Optical system **100** may also include a host computer **170** that may include a processor **174** configured to read and execute operations based on pre-programmed instructions **178** stored in a computer-readable medium **180**. Instructions **178** may include at least some instructions provided to controller **114** and stored in memory **116**. Host computer **170** may communicate with one or more elements of wearable device **110** over a signal and power bus **188**. In this manner, host computer **170** may provide power to charge battery **122**, provide instructions to and receive status from controller **114**, to control various other elements of wearable device **110**, and to provide digital image data to optical engine **126**.

[0036] FIG. **2** illustrates an end view of an image pipe, in accordance with various examples of the present disclosure. As illustrated in an idealized form, an image pipe **140** may be an elongated transparent member having a first end (e.g., background of FIG. **2**) and a second end (e.g., foreground of FIG. **2**) with a rectangular cross section with orthogonal walls. As a specific example, image pipe **140** may have a square cross section with orthogonal walls which may form four external faces. Image pipe **140** may be configured to receive an input image beam (not shown) that may be injected at an angle by an image projector **126**, for example. Image pipe **140** may provide four replicated output image beams **204-210** based on the injected image beam. As light from the injected image propagates along waveguide **140** while being reflected from all four external faces, four conjugate image beams (e.g., image beam vectors) may be generated **202-208** which represent the same image as it is reflected internally by the faces. Portions of or an entirety of one or more outer surfaces of image pipe **140** may be coated with partially or fully reflective coatings or a low refractive index (LRI) adhesive to promote conduction of an injected image beam and to reduce loss. Image pipe **140** may include a glass material, an acrylic material, and/or a polycarbonate material having the same or different index of refraction compared with other elements in system **100**, for example. Image pipe **140** may be attached to or integrated with one or more waveguide elements and may be considered to be an imbedded image pipe, as will be described more fully below.

[0037] FIGS. **3**A-**3**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **3**A illustrates a front plan view of an optical device **302**, FIG. **3**B illustrates a side plan view of a portion of optical device **302**, and FIG. **3**C illustrates an enlarged view **304** of a portion of optical device **302**, in accordance with various examples of the present disclosure. In FIG. **3**A and elsewhere, an eye **308** and a nose **309** of a user may be illustrated to provide a reference for how optical system **302** may be worn on a head of a user and used to provide optical information, as described.

[0038] According to an example, an optical device **302** may include a coupling assembly **320**, an image pipe **360**, a first waveguide **376**, and a second waveguide **388**. Coupling assembly **320** may be similar in some ways to coupling assembly **136** of FIG. **1**. Coupling assembly **320** may be configured to receive a collimated image beam **310** (e.g., an "i" image beam) from projecting optical device **132** and provide a first output image beam **312** (e.g., a "j" image beam) and a second output image beam **314** (e.g., a "k" image beam). As used herein, the beams i, j, and k may denote projections of the beams along an image pipe where the beams may propagate at oblique angles with relation to a side of the image pipe, for example. As shown in various figures, the beams may denote the projection of the propagation direction of a collimated beam that may be associated with a single field within a field of view. In particular, coupling assembly **320** may include a passive optical element such as a cube beam splitter or a semitransparent mirror **322** having a first side **324** oriented toward projecting optical device **132**, and a second side **326** that is opposite first side **324** and oriented toward a first waveguide injection region WIR**31** of first waveguide **376**, for example. In this manner, collimated image beam **310** may be applied to semitransparent mirror **322** first side **324** as an input beam to coupling assembly **320** which may partially reflect a portion of collimated image beam **310** to be emitted from coupling assembly **320** as first output image beam **312** and semitransparent mirror **322** may partially transmit a portion of collimated image beam **310** to be emitted from coupling assembly **320** as second output image beam **314**.

[0039] Image pipe **360** may be similar in some ways to image pipe(s) **140** described in reference to FIG. **1** and FIG. **2**. Image pipe **360** may be configured to receive first output image beam **312** at an image pipe input **362** (e.g., image pipe **360** first end) and provide at least one propagated image beam **364** at an image pipe output **366** (e.g., image pipe **360** second end). First waveguide **376** may have a first waveguide front surface **383** that is parallel with a first waveguide rear surface **384**. First waveguide **376** may be configured to receive second output image beam **314** and emit a first expanded output image beam **386** from first waveguide rear surface **384**. As described, the terms first, second, third, and the like may be assigned to designate distinct elements and associations but could be assigned differently or changed depending on a particular example. Similar in some ways to first waveguide **376**, second waveguide **388** may have a second waveguide front surface **395** and a second waveguide rear surface **396**. Second waveguide **388** may be configured to receive the at least one propagated image beam **364** from image pipe **360** and emit a second expanded output image beam **398** from second waveguide rear surface **396**.

[0040] First waveguide **376** (labeled as "A") may include a first waveguide first aperture expander **378** and a first waveguide second aperture expander **380** separated from each other by a first waveguide dividing region **382**. First waveguide first aperture expander **378** may include a first plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **383** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **383**. First waveguide first aperture expander **378** may also include embedded volume or surface optical diffractive elements. Illumination from the second output image beam **314** may be received in a first direction (e.g., along a central axis of first waveguide aperture expander **378**) and then reflected in a second direction and propagated within first waveguide **376** as a first waveguide first plurality of expanded image beams X3A**1** that may be directed to first waveguide second aperture expander **380**. In this manner, second output image beam **314** illumination may be expanded in a first dimension by the spaced apart facets of first waveguide aperture expander **378** to provide the first plurality of expanded image beams X3A**1**. A reflectivity of the first plurality of partially reflecting facets in first waveguide first aperture expander **378** may increase in a direction away from waveguide injection region WIR**31**, where the first waveguide first aperture expander **378** may have an initial facet with a lowest reflectivity and may terminate with a final facet (e.g., a terminal facet) that may be highly reflective, and may be a fully reflective mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**31** and, separate from this feature, may terminate with a final facet that may or may not be a mirror. A portion of first waveguide **376** may be affixed to a portion of image pipe **360** with any of the following: a layer of low refractive index (LRI) adhesive **306**, a layer of low refractive index coating, or a thin film coating that assures total (or nearly total) internal reflection (TIR). Alternatively, the first waveguide **376** may be air-spaced from image pipe **360**. These alternatives may also apply to the various examples disclosed herein.

[0041] Similarly, first waveguide second aperture expander **380** may include a second plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **383** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **383**. Illumination from the first plurality of expanded image beams X3A**1** may be received in the second direction and then reflected in a third direction toward first waveguide rear surface **384** by the second plurality of partially reflecting optical elements in first waveguide second aperture expander **380**. In this manner, illumination from first plurality of expanded image beams X3A**1** may be expanded in a second dimension by the spaced apart facets of first waveguide second aperture expander **380** to provide the second plurality of expanded image beams X3A**2**. The plurality of expanded image beams X3A1 may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X3A2. Thus, the first waveguide first aperture expander **378** and the first waveguide second aperture expander **380** may cooperate to provide a two-dimensional (2D) expansion of second output image beam **314** illumination as a first expanded output image beam **386** that may be emitted from first waveguide rear surface **384**. Similar to first waveguide first aperture expander **378**, a reflectivity of the second plurality of partially reflecting facets in first waveguide second aperture expander **380** may increase in a direction away from first waveguide first aperture expander **378**, where the first waveguide second aperture expander **380** may have an initial facet with a lowest reflectivity and a final facet (e.g., a terminal facet) that may be a mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from first waveguide first aperture expander **378** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0042] Second waveguide **388** (labeled as "B") may include a second waveguide first aperture expander **390** and a second waveguide second aperture expander **392** separated from each other by a second waveguide dividing region **394**. Second waveguide **388** may also include a mirror **356** configured to receive the at least one propagated image beam **364** and provide a reflected at least one propagated image beam **365**. Second waveguide first aperture expander **390** may include a third plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **395** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **395**. Second waveguide first aperture expander **390** may also include an embedded volume or surface optical diffractive elements. Illumination from the reflected at least one propagated image beam **365** may be received in a fourth direction (e.g., along a central axis of the second waveguide aperture expander **390**) and then reflected in a fifth direction by the first plurality of partially reflecting optical elements in second waveguide first aperture expander **390** and conducted within second waveguide **388** as a second waveguide first plurality of expanded image beams X3B1 that may be directed to second waveguide second aperture expander **392**. In this manner, the reflected at least one propagated image beam **365** illumination may be expanded in a first dimension (e.g., a third dimension) by the spaced apart facets to provide the first plurality of expanded image beams X3B1. A reflectivity of the third plurality of partially reflecting facets in second waveguide first aperture expander **390** may increase in a direction away from a second waveguide injection region WIR32, where the second waveguide first aperture expander **390** may have an initial facet with a lowest reflectivity and may terminate with a final facet (e.g., a terminal facet) that may highly reflective, or may be a mirror. Alternatively, a reflectivity of the third plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR32 and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0043] Similarly, second waveguide second aperture expander **392** may include a fourth plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **395** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **395**. Second waveguide second aperture expander **392** may also include embedded volume or surface optical diffractive elements. Illumination from the third plurality of expanded image beams X3B1 may be received in the fifth direction and then reflected in a sixth direction toward second waveguide rear surface **396** by the fourth plurality of partially reflecting optical elements in second waveguide second aperture expander **392**. In this manner, illumination from third plurality of expanded image beams X3B1 may be expanded in a second dimension (e.g., a fourth dimension) by the spaced apart facets of second waveguide second aperture expander **392** to provide the second plurality of expanded image beams X3B2. The plurality of expanded image beams X3B1 may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X3B2. Thus, the second waveguide first aperture expander **390** and the second waveguide second aperture expander **392** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one propagated image beam **365** illumination as a second expanded output image beam **398** that may be emitted from second waveguide rear surface **396**. Similar to second waveguide first aperture expander **390**, a reflectivity of the fourth plurality of partially reflecting facets in second waveguide second aperture expander **392** may increase in a direction away from second waveguide first aperture expander **390**, where the second waveguide second aperture expander **392** may have an initial facet with a lowest reflectivity and a final facet (e.g., a terminal facet) that may be highly reflective and may be a mirror. Alternatively, a reflectivity of the fourth plurality of partially reflecting facets may be constant in a direction away from second waveguide first aperture expander **390** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0044] As described above, image projector **132** may provide a collimated image beam **310** (e.g., a collimated single field) that may be an illuminated representation of the digital image having an image field which is a two-dimensional representation of the digital image. In this manner, the image field may have a vertical and/or lateral extent, as illustrated in FIG. **3**A, and elsewhere. For example, first output image beam **312** may propagate through image pipe **360** and into second waveguide **388** having a vertical extent (labeled as "C" and "D"), reflected by mirror **356**, and then reflected by second waveguide first aperture expander **390**. In this manner, a single pixel on the image may correspond with a collimated beam and a single beam. Accordingly, beams C and D may be laterally displaced beams with the same orientation (e.g., the lines are parallel), and therefore they may be associated with the same field, for example. The extension of beams described herein may not relate to an extension of an output image that may be observed by a user. Similarly, second output image beam **314** may propagate into first waveguide **376** having a lateral extent (labeled as "C" and "D") and reflected by first waveguide first aperture expander **378**. Thus, first output image beam **312** and second output image beam **314** and others may propagate through various optical elements in optical system **100** as a two-dimensional (2D) image field about the illustrated central axes. In some examples, mirror **356** may not be used.

[0045] According to an example, first waveguide first aperture expander **378** and second waveguide first aperture expander **390** may be oriented parallel to each other. Further, second waveguide first aperture expander **390** may be disposed on a side of second waveguide **388** that is closest to (e.g., proximal to) first waveguide **376**, as shown in FIG. **3**A. Other arrangements are also possible, where second waveguide first aperture expander **390** may be disposed on a side of second waveguide **388** that is farthest from (e.g., distal from) first waveguide **376**. As mentioned briefly above, beams drawn in the various figures may denote the projection of the propagation direction of a collimated beam that is associated with a single field within the field of view (FoV). In a practical system, within the first or second waveguide these beams may be ascending and descending beams that may be trapped in the waveguides by total internal reflection (TIR). Within an image pipe, the beams may be ascending right, ascending left, descending right and descending left.

[0046] FIGS. **4**A-**4**B illustrate details regarding an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **4**A illustrates a front plan view of an optical device **402**, and FIG. **4**B illustrates an enlarged view **404** of a portion of optical device **402**, in accordance with various examples of the present disclosure.

[0047] According to an example, an optical device **402** may include a coupling assembly **420**, an image pipe **460**, a first waveguide **476**, and a second waveguide **488**. Coupling assembly **420** may be similar in some ways to coupling assembly **136** of FIG. **1**. Coupling assembly **420** may be configured to receive a collimated image beam **410** (e.g., an "i" image beam) from projecting optical device **132** and provide a first output image beam **412** (e.g., a "j" image beam) and a second output image beam **414** (e.g., a "k" image beam). In particular, coupling assembly **420** may include a passive optical element such as a polarizing beam splitter (PBS) **422** having a first side **424** oriented toward projecting optical device **132**, and a second side **426** that is opposite first side **424** and oriented toward a first waveguide injection region WIR**41** of first waveguide **476**, for example. In this manner, collimated image beam **410** may be applied to polarizing beam splitter **422** first side **424** as an input beam to coupling assembly **420** which may partially reflect a portion of collimated image beam **410** to be emitted from coupling assembly **420** as first output image beam **412** and polarizing beam splitter **422** may partially transmit a portion of collimated image beam **410** to be emitted from polarizing beam splitter **424** second side **426** as transmitted image beam **428**.

[0048] Collimated image beam **410** may include polarized illumination. Polarizing beam splitter **422** may include a wire grid, crystal, directional polymer, or dielectric material that reflects S polarization (e.g., perpendicular) but transmits P polarization (e.g., parallel), or vice versa. Hence, polarizing beam splitter may receive collimated image beam **410** and provide first output beam **412** as an S-polarized image beam and transmitted image beam **428** as a P-polarized image beam. Coupling assembly **420** may also include a half wave plate (HWP) **430** having a half wave plate first side **432** and a half wave plate second side **434**. Half wave plate **430** may include a crystal or dielectric material configured to retard (e.g., delay) one component of polarization to transmit light and modify polarization without attenuating, deviating, or displacing the incident beam. Thus, half wave plate **430** first side **432** may receive transmitted beam **428** and provide second output image beam **414** from half wave plate **430** second side **434**. In this example, transmitted beam **428** is P-polarized by passing through polarizing beam splitter **422**, and second output image beam **414** is converted to S-polarization by passing through half wave plate **430** so that both first output beam **412** and second output beam **414** have the same S-polarization.

[0049] Image pipe **460** may be similar in some ways to image pipe(s) **140** described in reference to FIG. **1** and FIG. **2**. Image pipe **460** may be configured to receive first output image beam **412** at an image pipe input **462** (e.g., image pipe **460** first end) and provide at least one propagated image beam **464** at an image pipe output **466** (e.g., image pipe **460** second end). First waveguide **476** may have a first waveguide front surface **483** that is parallel with a first waveguide rear surface **484**. First waveguide **476** may be configured to receive second output image beam **414** and emit a first expanded output image beam **486** from first waveguide rear surface **484**. Similar in some ways to first waveguide **476**, second waveguide **488** may have a second waveguide front surface **495** and a second waveguide rear surface **496**. Second waveguide **488** may be configured to receive the at least one propagated image beam **464** from image pipe **460** and emit a second expanded output image beam **498** from second waveguide rear surface **396**.

[0050] First waveguide **476** (labeled as "A") may include a first waveguide first aperture expander **478** and a first waveguide second aperture expander **480** separated from each other by a first waveguide dividing region **482**. First waveguide first aperture expander **478** may include a first plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **483** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **483**. Illumination from the second output image beam **414** may be received in a first direction (e.g., along a central axis of first waveguide aperture expander **478**) and then reflected in a second direction and propagated within first waveguide **476** as a first waveguide first plurality of expanded image beams X**4**A**1** that may be directed to first waveguide second aperture expander **480**. In this manner, second output image beam **414** illumination may be expanded in a first dimension by the spaced apart facets of first waveguide aperture expander **478** to provide the first plurality of expanded image beams X**4**A**1**. A reflectivity of the first plurality of partially reflecting facets in first waveguide first aperture expander **478** may increase in a direction away from waveguide injection region WIR**41**, where the first waveguide first aperture expander **478** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a fully reflective mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**41** and, separate from this feature, may terminate with a final facet that may or may not be a mirror. A portion of first waveguide **476** may be affixed to a portion of image pipe **460** with a layer of low refractive index (LRI) adhesive **406**.

[0051] Similarly, first waveguide second aperture expander **480** may include a second plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **483** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **483**. Illumination from the first plurality of expanded image beams X**4**A**1** may be received in the second direction and then reflected in a third direction toward first waveguide rear surface **484** by the second plurality of partially reflecting optical elements in first waveguide second aperture expander **480**. In this manner, illumination from first plurality of expanded image beams X**4**A**1** may be expanded in a second dimension by the spaced apart facets of first waveguide second aperture expander **480** to provide the second plurality of expanded image beams X**4**A**2**. The plurality of expanded image beams X**4**A**1** may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X**4**A**2**. Thus, the first waveguide first aperture expander **478** and the first waveguide second aperture expander **480** may cooperate to provide a two-dimensional (2D) expansion of second output image beam **414** illumination as a first expanded output image beam **486** that may be emitted from first waveguide rear surface **484**. Similar to first waveguide first aperture expander **478**, a reflectivity of the second plurality of partially reflecting facets in first waveguide second aperture expander **480** may increase in a direction away from first waveguide first aperture expander **478**, where the first waveguide second aperture expander **480** may have an initial facet with a lowest reflectivity and a final facet that may be a mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from first waveguide first aperture expander **478** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0052] Second waveguide **488** (labeled as "B") may include a second waveguide first aperture expander **490** and a second waveguide second aperture expander **492** separated from each other by a second waveguide dividing region **494**. Second waveguide first aperture expander **490** may include a third plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **495** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **495**. Illumination from the at least one propagated image beam **464** may be received in a fourth direction (e.g., along a central axis of the second waveguide aperture expander **490**) and then reflected in a fifth direction by the first plurality of partially reflecting optical elements in second waveguide first aperture expander **490** and conducted within second waveguide **488** as a second waveguide first plurality of expanded image beams X**4**B**1** that may be directed to second waveguide second aperture expander **492**. In this manner, the at least one propagated image beam **464** illumination may be expanded in a first dimension (e.g., a third dimension) by the spaced apart facets to provide the first plurality of expanded image beams X**4**B**1**. A reflectivity of the third plurality of partially reflecting facets in second waveguide first aperture expander **490** may increase in a direction away from a second waveguide injection region WIR**42**, where the second waveguide first aperture expander **490** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a mirror. Alternatively, a reflectivity of the third plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**42** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0053] Similarly, second waveguide second aperture expander **492** may include a fourth plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **495** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **495**. Illumination from the third plurality of expanded image beams X**4**B**1** may be received in the fifth direction and then reflected in a sixth direction toward second waveguide rear surface **496** by the fourth plurality of partially reflecting optical elements in second waveguide second aperture expander **492**. In this manner, illumination from third plurality of expanded image beams X**4**B**1** may be expanded in a second dimension (e.g., a fourth dimension) by the spaced apart facets of second waveguide second aperture expander **492** to provide the second plurality of expanded image beams X**4**B**2**. In this manner, the plurality of expanded image beams X**4**B**1** may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X**4**B**2**. Thus, the second waveguide first aperture expander **490** and the second waveguide second aperture expander **492** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one propagated image beam **464** illumination as a second expanded output image beam **498** that may be emitted from second waveguide rear surface **496**. Similar to second waveguide first aperture expander **490**, a reflectivity of the fourth plurality of partially reflecting facets in second waveguide second aperture expander **492** may increase in a direction away from second waveguide first aperture expander **490**, where the second waveguide second aperture expander **492** may have an initial facet with a lowest reflectivity and a final facet (e.g., a terminal facet) that is a mirror. Alternatively, a reflectivity of the fourth plurality of partially reflecting facets may be constant in a direction away from second waveguide first aperture expander **490** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0054] As described above, image projector **132** may provide a collimated image beam **410** that may be an illuminated representation of the digital image having an image field which is a two-dimensional representation of the digital image. Thus, first output image beam **412** and second output image beam **414** and others may propagate through various optical elements in optical system **100** as a two-dimensional (2D) image field about the illustrated central axes.

[0055] According to an example, first waveguide first aperture expander **478** and second waveguide first aperture expander **490** may be oriented perpendicular to each other. Other arrangements are also possible, where second waveguide first aperture expander **490** may be disposed on a side of second waveguide **488** that is farthest from (e.g., distal from) first waveguide **476**. In this case, second waveguide **488** and various components may be oppositely arranged (e.g., reflected, flipped, or rotated) about a diagonal axis **458**

where second input aperture **490** may be arranged vertically above or below diagonal axis **458** as compared with FIG. 3A, for example.

[0056] According to an example, coupling assembly **420** may also include an active half wave plate liquid crystal element (AHWP) **448** configured to receive the collimated image beam **410** and provide a transformed image beam **450**. Active half wave plate liquid crystal element **448** may be an active optical element controlled by signals from controller **114** to selectively change polarity of at least a portion of collimated image beam **410** and provide transformed image beam **450**, such as changing from an S-polarization to a P-polarization when activated, for example. In this example, polarizing beam splitter **422** first side **424** may receive transformed image beam **450** and provide first output image beam **412** from polarizing beam splitter **422** first side **424** and provide transmitted beam **428** from polarizing beam splitter second side **426**. In this manner, optical device **402** may be practiced with or without active half wave plate liquid crystal element **448**.

[0057] FIGS. **5**A-**5**B illustrate details regarding an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **5**A illustrates a front plan view of an optical device **502**, and FIG. **5**B illustrates an enlarged view **504** of a portion of optical device **502**, in accordance with various examples of the present disclosure.

[0058] According to an example, an optical device **502** may include a coupling assembly **520**, an image pipe **560**, a first waveguide **576**, and a second waveguide **588**. Coupling assembly **520** may be similar in some ways to coupling assembly **136** of FIG. **1**. As mentioned above, like reference numbers and like element names may indicate identical or functionally similar elements. For example, coupling assembly **520** may be similar in some ways to coupling assembly **320** described in reference to FIG. **3**A, and coupling assembly **520** may be similar in some ways to coupling assembly **420** described in reference to FIG. **4**A, for example. Coupling assembly **520** may be configured to receive a collimated image beam **510** (e.g., an "i" image beam) from projecting optical device **132** and provide a first output image beam **512** (e.g., a "j" image beam) and a second output image beam **514** (e.g., a "k" image beam). In particular, coupling assembly **520** may include a passive optical element such as a polarizing beam splitter (PBS) **522** having a first side **524** oriented toward projecting optical device **132**, and a second side **526** that is opposite first side **524** and oriented toward a first waveguide injection region WIR**51** of first waveguide **576**, for example. In this manner, collimated image beam **510** may be applied to polarizing beam splitter **522** first side **524** as an input beam to coupling assembly **520** which may partially reflect a portion of collimated image beam **510** to be emitted from coupling assembly **520** as first output image beam **512** and polarizing beam splitter **522** may partially transmit a portion of collimated image beam **510** to be emitted from polarizing beam splitter **524** second side **526** as transmitted image beam **528**. Collimated image beam **510** may include polarized illumination. Polarizing beam splitter **522** may include a wire grid, crystal, or dielectric material that reflects S polarization (e.g., perpendicular) but transmits P polarization (e.g., parallel). Hence, polarizing beam splitter may receive collimated image beam **510** and provide first output beam **512** as an S-polarized image beam and transmitted image beam **528** as a P-polarized image beam. Coupling assembly **520** may also include a half wave plate (HWP) **530** having a half wave plate first side **532** and a half wave plate second side **534**. Half wave plate **530** may include a crystal or dielectric material configured to retard (e.g., delay) one component of polarization to transmit light and modify polarization without attenuating, deviating, or displacing the incident beam. Thus, half wave plate **530** first side **532** may receive transmitted beam **528** and provide second output image beam **514** from half wave plate **530** second side **534**. In this example, transmitted beam **528** is P-polarized by passing through polarizing beam splitter **522**, and second output image beam **514** is converted to S-polarization by passing through half wave plate **530** so that both first output beam **512** and second output beam **514** have the same S-polarization.

[0059] Image pipe **560** may be similar in some ways to image pipe(s) **140** described in reference to FIG. **1** and FIG. **2**. Image pipe **560** may be configured to receive first output image beam **512** at an image pipe input **562** (e.g., image pipe **560** first end) and provide at least one propagated image beam **564** at an image pipe output **566** (e.g., image pipe **560** second end). First waveguide **576** may have a first waveguide front surface **583** that is parallel with a first waveguide rear surface **584**. First waveguide **576** may be configured to receive second output image beam **514** and emit a first expanded output image beam **586** from first waveguide rear surface **584**. Similar in some ways to first waveguide **576**, second waveguide **588** may have a second waveguide front surface **595** and a second waveguide rear surface **596**. Second waveguide **588** may be configured to receive the at least one propagated image beam **564** from image pipe **560** and emit a second expanded output image beam **598** from second waveguide rear surface **396**.

[0060] First waveguide **576** (labeled as "A") may include a first waveguide first aperture expander **578** and a first waveguide second aperture expander **580** separated from each other by a first waveguide dividing region **582**. First waveguide first aperture expander **578** may include a first plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **583** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **583**. Illumination from the second output image beam **514** may be received in a first direction (e.g., along a central axis of first waveguide aperture expander **578**) and then reflected in a second direction and propagated within first waveguide **576** as a first waveguide first plurality of expanded image beams X**5**A**1** that may be directed to first waveguide second aperture expander **580**. In this manner, second output image beam **514** illumination may be expanded in a first dimension by the spaced apart facets of first waveguide aperture expander **578** to provide the first plurality of expanded image beams X**5**A**1**. A reflectivity of the first plurality of partially reflecting facets in first waveguide first aperture expander **578** may increase in a direction away from waveguide injection region WIR**51**, where the first waveguide first aperture expander **578** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a fully reflective mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**51** and, separate from this feature, may terminate with a final facet that may or may not be a mirror. A portion of first waveguide **576** may be affixed to a portion of image pipe **560** with a layer of low refractive index (LRI) adhesive **506**.

[0061] Similarly, first waveguide second aperture expander **580** may include a second plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **583** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **583**. Illumination from the first plurality of expanded image beams X5A1 may be received in the second direction and then reflected in a third direction toward first waveguide rear surface **584** by the second plurality of partially reflecting optical elements in first waveguide second aperture expander **580**. In this manner, illumination from first plurality of expanded image beams X5A1 may be expanded in a second dimension by the spaced apart facets of first waveguide second aperture expander **580** to provide the second plurality of expanded image beams X5A2. The plurality of expanded image beams X5A1 may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X5A2. Thus, the first waveguide first aperture expander **578** and the first waveguide second aperture expander **580** may cooperate to provide a two-dimensional (2D) expansion of second output image beam **514** illumination as a first expanded output image beam **586** that may be emitted from first waveguide rear surface **584**. Similar to first waveguide first aperture expander **578**, a reflectivity of the second plurality of partially reflecting facets in first waveguide second aperture expander **580** may increase in a direction away from first waveguide first aperture expander **578**, where the first waveguide second aperture expander **580** may have an initial facet with a lowest reflectivity and a final facet that may be a mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from first waveguide first aperture expander **578** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0062] Second waveguide **588** (labeled as "B") may include a second waveguide first aperture expander **590** and a second waveguide second aperture expander **592** separated from each other by a second waveguide dividing region **594**. Second waveguide **588** may also include a mirror **556** configured to receive the at least one propagated image beam **564** and provide a reflected at least one propagated image beam **565**. Second waveguide first aperture expander **590** may include a third plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **595** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **595**. Illumination from the reflected at least one propagated image beam **565** may be received in a fourth direction (e.g., along a central axis of the second waveguide aperture expander **590**) and then reflected in a fifth direction by the first plurality of partially reflecting optical elements in second waveguide first aperture expander **590** and conducted within second waveguide **588** as a second waveguide first plurality of expanded image beams X5B1 that may be directed to second waveguide second aperture expander **592**. In this manner, the reflected at least one propagated image beam **565** illumination may be expanded in a first dimension (e.g., a third dimension) by the spaced apart facets to provide the first plurality of expanded image beams X5B1. A reflectivity of the third plurality of partially reflecting facets in second waveguide first aperture expander **590** may increase in a direction away from a second waveguide injection region WIR52, where the second waveguide first aperture expander **590** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a mirror. Alternatively, a reflectivity of the third plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR52 and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0063] Similarly, second waveguide second aperture expander **592** may include a fourth plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **595** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **595**. Illumination from the third plurality of expanded image beams X5B1 may be received in the fifth direction and then reflected in a sixth direction toward second waveguide rear surface **596** by the fourth plurality of partially reflecting optical elements in second waveguide second aperture expander **592**. In this manner, illumination from third plurality of expanded image beams X5B1 may be expanded in a second dimension (e.g., a fourth dimension) by the spaced apart facets of second waveguide second aperture expander **592** to provide the second plurality of expanded image beams X5B2. In this manner, the plurality of expanded image beams X5B1 may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X5B2. Thus, the second waveguide first aperture expander **590** and the second waveguide second aperture expander **592** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one propagated image beam **565** illumination as a second expanded output image beam **598** that may be emitted from second waveguide rear surface **596**. Similar to second waveguide first aperture expander **590**, a reflectivity of the fourth plurality of partially reflecting facets in second waveguide second aperture expander **592** may increase in a direction away from second waveguide first aperture expander **590**, where the second waveguide second aperture expander **592** may have an initial facet with a lowest reflectivity and a final facet (e.g., a terminal facet) that is a mirror. Alternatively, a reflectivity of the fourth plurality of partially reflecting facets may be constant in a direction away from second waveguide first aperture expander **590** and, separate from this feature, may terminate with a final facet that may or may not be a mirror. As described above, image projector **132** may provide a collimated image beam **510** that may be an illuminated representation of the digital image having an image field which is a two-dimensional representation of the digital image. Thus, first output image beam **512** and second output image beam **514** and others may propagate through various optical elements in optical system **100** as a two-dimensional (2D) image field about the illustrated central axes. A portion of second waveguide **588** may be affixed to a portion of image pipe **560** with a layer of low refractive index (LRI) adhesive **516**.

[0064] According to an example, first waveguide first aperture expander **578** and second waveguide first aperture expander **590** may be oriented parallel to each other. Other arrangements are also possible, where second waveguide first aperture expander **590** may be disposed on a side of second waveguide **588** that is farthest from (e.g., distal from) first waveguide **576**. In this case, second waveguide **588** may be oppositely arranged about a vertical axis **546** where second input aperture **590** may be arranged horizontally left or right of second waveguide second aperture **592** as compared with FIG. **3**A, for example.

[0065] According to an example, coupling assembly **520** may also include an active half wave plate liquid crystal element (AHWP) **548** configured to receive the collimated image beam **510** and provide a transformed image beam **550**. Active half wave plate liquid crystal element **548** may be an active optical element controlled by signals from controller **114** to selectively change polarity of at least a portion of collimated image beam **510** and provide transformed image beam **550**, such as changing from an S-polarization to a P-polarization when activated, for example. In this example, polarizing beam splitter **522** first side **524** may receive transformed image beam **550** and provide first output image beam **512** from polarizing beam splitter **522** first side **524** and provide transmitted beam **528** from polarizing beam splitter second side **526**. In this manner, optical device **502** may be practiced with or without active half wave plate liquid crystal element **548**. Coupling assemblies **420** and **520** may include various active or passive optical elements as described. In the system illustrated in FIG. **4** and FIG. **5**, an image may be rotated between the first waveguide and the second waveguide. In a practical system, in order to avoid introduction of a possibly 50% flipped, ghost image, the image provided by the image projector may be rotated.

[0066] FIGS. **6**A-**6**B illustrate details regarding an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **6**A illustrates a front plan view of an optical device **602**, and FIG. **6**B illustrates an enlarged view **604** of a portion of optical device **602**, in accordance with various examples of the present disclosure.

[0067] According to an example, an optical device **602** may include a coupling assembly **620**, a first image pipe **660**, a second image pipe **668**, a first waveguide **676**, and a second waveguide **688**. Coupling assembly **620** may be similar in some ways to coupling assembly **136** of FIG. **1**. Coupling assembly **620** may be configured to receive a collimated image beam **610** (e.g., an "i" image beam) from projecting optical device **132** and provide a first output image beam **612** (e.g., a "j" image beam) and a second output image beam **614** (e.g., a "k" image beam). Collimated image beam **610** may include polarized illumination. In particular, coupling assembly **620** may include a passive optical element such as a polarizing beam splitter (PBS) **622** having a first side **624** oriented toward projecting optical device **132**, and a second side **626** that is opposite first side **624** and oriented on a side away from projecting optical device **132**, for example. In this manner, collimated image beam **610** may be applied to polarizing beam splitter **622** first side **624** as an input beam to coupling assembly **620** which may partially reflect a portion of collimated image beam **610** to be emitted from coupling assembly **620** as first output image beam **612** having S-polarization, and polarizing beam splitter **622** may partially transmit a portion of collimated image beam **610** to be emitted from polarizing beam splitter **624** second side **626** having P-polarization as transmitted image beam **628**. Polarizing beam splitter **622** may include a wire grid, crystal, directional polymer, or dielectric material that reflects S polarization (e.g., perpendicular) but transmits P polarization (e.g., parallel). Hence, polarizing beam splitter may receive collimated image beam **610** and provide first output beam **612** as an S-polarized image beam and transmitted image beam **628** as a P-polarized image beam. Coupling assembly **620** may also include a quarter wave plate (QWP) **630** having a quarter wave plate first side **632** and a quarter wave plate second side **634**. Quarter wave plate **630** may include a crystal or dielectric material configured to convert linearly polarized light into circularly polarized light and convert circularly polarized light into linearly polarized light (e.g., S-polarization or P-polarization). Thus, quarter wave plate **630** first side **632** may receive transmitted beam **628** at quarter wave plate **630** first side **632** and provide a first converted image beam **636** at quarter wave plate **630** second side **634**. Coupling assembly **630** may also include a mirror **638** having a fully reflective surface **640** that is disposed adjacent to quarter wave plate second side **634** and configured to receive and reflect first converted beam **636** as a reflected image beam **642**. Quarter wave plate **630** may receive reflected image beam **642** at quarter wave plate **630** second side **634** and provide a second converted image beam **644** to be emitted from quarter wave plate **630** first side **632**. Polarizing beam splitter **622** second side **626** may receive second converted image beam **644** and provide a reflected second output beam **614** having S-polarization. In this manner, the first output beam **612** and the second output beam **614** may have the same S-polarization. One technical benefit provided by the sequence of transformations described above is that they support a passive system (e.g., a system with passive elements) and a symmetrical structure which may facilitate simpler design of an eye box location in relation to a nose of a user, for example.

[0068] First image pipe **660** and second image pipe **668** may be similar in some ways to image pipe(s) **140** described in reference to FIG. **1** and FIG. **2**. First image pipe **660** may be configured to receive first output image beam **612** at an image pipe input **662** (e.g., first image pipe **660** first end) and provide at least one first propagated image beam **664** at a first image pipe output **666** (e.g., first image pipe **660** second end). Second image pipe **668** may be configured to receive second output image beam **614** at a second image pipe input **670** (e.g., second image pipe **668** first end) and provide at least one second propagated image beam **672** at a second image pipe output **674** (e.g., second image pipe **668** second end). In this manner, coupling assembly **620** may be considered to be integrated or embedded with the first image pipe **660** and second image pipe **668**.

[0069] First waveguide **676** may have a first waveguide front surface **683** that is parallel with a first waveguide rear surface **684**. First waveguide **676** may also include a first mirror **654** configured to receive the at least one second propagated image beam **672** and provide a reflected at least one second propagated image beam **673** at a first waveguide injection region WIR**61**. First waveguide **676** may be configured to receive the reflected at least one second propagated image beam **673** and emit a first expanded output image beam **686** from first waveguide rear surface **684**. Similar in some ways to first waveguide **676**, second waveguide **688** may have a second waveguide front surface **695** and a second waveguide rear surface **696**. Second waveguide **688** may also include a second mirror **656** configured to receive the at least one first propagated image beam **664** and provide a reflected at least one first propagated image beam **665** at a second waveguide injection region WIR**62**. Second waveguide **688** may be configured to receive the reflected at least one first propagated image beam **665** and emit a second expanded output image beam **698** from second waveguide rear surface **396**.

[0070] First waveguide **676** (labeled as "A") may include a first waveguide first aperture expander **678** and a first waveguide second aperture expander **680** separated from each other by a first waveguide dividing region **682**. First waveguide first aperture expander **678** may include a first plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **683** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **683**. Illumination from the reflected at least one second propagated image beam **673** may be received in a first direction (e.g., along a central axis of first waveguide aperture expander **678**) and then reflected in a second direction and propagated within first waveguide **676** as a first waveguide first plurality of expanded image beams X**6**A**1** that may be directed to first waveguide second aperture expander **680**. In this manner, the reflected at least one second propagated image beam **673** illumination may be expanded in a first dimension by the spaced apart facets of first waveguide aperture expander **678** to provide the first plurality of expanded image beams X**6**A**1**. A reflectivity of the first plurality of partially reflecting facets in first waveguide first aperture expander **678** may increase in a direction away from waveguide injection region WIR**61**, where the first waveguide first aperture expander **678** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a fully reflective mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**61** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0071] Similarly, first waveguide second aperture expander **680** may include a second plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **683** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **683**. Illumination from the first plurality of expanded image beams X**6**A**1** may be received in the second direction and then reflected in a third direction toward first waveguide rear surface **684** by the second plurality of partially reflecting optical elements in first waveguide second aperture expander **680**. In this manner, illumination from first plurality of expanded image beams X**6**A**1** may be expanded in a second dimension by the spaced apart facets of first waveguide second aperture expander **680** to provide the second plurality of expanded image beams X**6**A**2**. The plurality of expanded image beams X**6**A**1** may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X**6**A**2**. Thus, the first waveguide first aperture expander **678** and the first waveguide second aperture expander **680** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one second propagated image beam **673** illumination as a first expanded output image beam **686** that may be emitted from first waveguide rear surface **684**. Similar to first waveguide first aperture expander **678**, a reflectivity of the second plurality of partially reflecting facets in first waveguide second aperture expander **680** may increase in a direction away from first waveguide first aperture expander **678**, where the first waveguide second aperture expander **680** may have an initial facet with a lowest reflectivity and a final facet that may be a mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from first waveguide first aperture expander **678** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0072] Second waveguide **688** (labeled as "B") may include a second waveguide first aperture expander **690** and a second waveguide second aperture expander **692** separated from each other by a second waveguide dividing region **694**. Second waveguide first aperture expander **690** may include a third plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **695** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **695**. Illumination from the reflected at least one propagated image beam **665** may be received in a fourth direction (e.g., along a central axis of the second waveguide aperture expander **690**) and then reflected in a fifth direction by the first plurality of partially reflecting optical elements in second waveguide first aperture expander **690** and conducted within second waveguide **688** as a second waveguide first plurality of expanded image beams X**6**B**1** that may be directed to second waveguide second aperture expander **692**. In this manner, the reflected at least one propagated image beam **665** illumination may be expanded in a first dimension (e.g., a third dimension) by the spaced apart facets to provide the first plurality of expanded image beams X**6**B**1**. A reflectivity of the third plurality of partially reflecting facets in second waveguide first aperture expander **690** may increase in a direction away from a second waveguide injection region WIR**62**, where the second waveguide first aperture expander **690** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a mirror. Alternatively, a reflectivity of the third plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**62** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0073] Similarly, second waveguide second aperture expander **692** may include a fourth plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **695** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **695**. Illumination from the third plurality of expanded image beams X**6**B**1** may be received in the fifth direction and then reflected in a sixth direction toward second waveguide rear surface **696** by the fourth plurality of partially reflecting optical elements in second waveguide second aperture expander **692**. In this manner, illumination from third plurality of expanded image beams X6B1 may be expanded in a second dimension (e.g., a fourth dimension) by the spaced apart facets of second waveguide second aperture expander **692** to provide the second plurality of expanded image beams X6B2. In this manner, the plurality of expanded image beams X6B1 may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X6B2. Thus, the second waveguide first aperture expander **690** and the second waveguide second aperture expander **692** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one propagated image beam **665** illumination as a second expanded output image beam **698** that may be emitted from second waveguide rear surface **696**. Similar to second waveguide first aperture expander **690**, a reflectivity of the fourth plurality of partially reflecting facets in second waveguide second aperture expander **692** may increase in a direction away from second waveguide first aperture expander **690**, where the second waveguide second aperture expander **692** may have an initial facet with a lowest reflectivity and a final facet (e.g., a terminal facet) that is a mirror. Alternatively, a reflectivity of the fourth plurality of partially reflecting facets may be constant in a direction away from second waveguide first aperture expander **690** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0074] As described above, image projector **132** may provide a collimated image beam **610** that may be an illuminated representation of the digital image having an image field which is a two-dimensional representation of the digital image. Thus, first output image beam **612** and second output image beam **614** and others may propagate through various optical elements in optical system **100** as a two-dimensional (2D) image field about the illustrated central axes.

[0075] According to an example, first waveguide first aperture expander **678** and second waveguide first aperture expander **690** may be oriented parallel to each other, or either may be oriented perpendicular to each other. Other arrangements are also possible, where second waveguide first aperture expander **690** may be disposed on a side of second waveguide **688** that is farthest from (e.g., distal from) first waveguide **676**. In this case, first waveguide **676** may be oppositely arranged about a diagonal axis **652** where first input aperture **678** may be arranged vertically above or below diagonal axis **652** as compared with FIG. **4**A, for example. Similarly, second waveguide **688** may be oppositely arranged about a diagonal axis **658** where second input aperture **690** may be arranged vertically above or below diagonal axis **658** as compared with FIG. **4**A, for example. Either first mirror **654** or second mirror **656** may include a coating configured to select two of the four images provided by the associated image pipe, for example. In some examples, first mirror **654** and/or second mirror **656** may not be used.

[0076] According to an example, coupling assembly **620** may also include an active half wave plate liquid crystal element (AHWP) **648** configured to receive the collimated image beam **610** and provide a transformed image beam **650**. Active half wave plate liquid crystal element **648** may be an active optical element controlled by signals from controller **114** to selectively change polarity of at least a portion of collimated image beam **610** and provide transformed image beam **650**, such as changing from an S-polarization to a P-polarization when activated, for example. In this example, polarizing beam splitter **622** first side **624** may receive transformed image beam **650** and provide first output image beam **612** from polarizing beam splitter **622** first side **624** and provide transmitted beam **628** from polarizing beam splitter second side **626**. In this manner, optical device **602** may be practiced with or without active half wave plate liquid crystal element **648**.

[0077] FIGS. **7**A-**7**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **7**A illustrates a front plan view of an optical system **702**, FIG. **7**B illustrates a first cross section of optical system **702** taken along an X-Z plane identified as cross section α (alpha), and FIG. **7**C illustrates a cross section of optical system **702** taken along a Y-Z plane identified as cross section β (beta), in accordance with various examples of the present disclosure.

[0078] According to an example, an optical device **702** may include an image pipe **760** integrated with a first waveguide **776** (Labeled as "A"). A portion of image pipe **760** may be affixed to a portion of first waveguide **776** using a low index of refraction (LRI) adhesive **706**, for example. First waveguide **776** may have a first waveguide front surface **783** that is parallel with a first waveguide rear surface **784**. In some examples, first waveguide **776** may directly receive a collimated image beam **710** (an "i" image beam) from a projecting optical device **132** to an image pipe input **762** of image pipe **760**. In an example, first waveguide **776** may also include a first mirror **751** (e.g., a semitransparent mirror) configured to receive the collimated image beam **710** and provide a reflected image beam **753** to image pipe input **762** as a first output image beam **712** (e.g., a "j" image beam) and provide a transmitted beam as a second output image beam **714** (e.g., a "k" image beam) that may be applied to another waveguide or other optical element, for example. As will be described below, first waveguide **776** may be mounted against a second waveguide, for example. Similar to the description above, directly injected image beam **710** or reflected image beam **753** may be propagated within image pipe **760** as at least one first propagated image beam **764** to image pipe output **766**. Within image pipe **760**, the at least one first propagated image beam **764** may be received from a first direction and may be reflected in a second direction by a second mirror **755** to provide a first reflected at least one first propagated image beam **757** which may be further reflected by a third mirror **754** in a third direction (e.g., opposite to the first direction) to provide a second reflected at least one first propagated image beam **764** at image pipe output **766** that may be injected into first waveguide **776** at a waveguide injection region WIR**71**. Mirror **755** may be oriented such that it is normal to the front and rear surfaces of the waveguide, and oriented at a 45° angle relative to the side planes of the associated image pipe as compared with an X-axis within the X-Y plane, for example. In this manner, image pipe **760** may have multiple segments and mirrors to propagate an image beam around a portion of first waveguide **776** to a waveguide injection region WIR**71** at a distance from projecting optical device **132**.

[0079] First waveguide **776** (labeled as "A") may include a first waveguide first aperture expander **778** and a first waveguide second aperture expander **780** separated from each other by a first waveguide dividing region **782**. First waveguide first aperture expander **778** may include a first plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **783** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **783**. Illumination from the reflected at least one first propagated image beam **764** may be received in a first direction (e.g., along a central axis of first waveguide aperture expander **778**) and then reflected in a second direction and propagated within first waveguide **776** as a first waveguide first plurality of expanded image beams X7A**1** that may be directed to first waveguide second aperture expander **780**. In this manner, the reflected at least one first propagated image beam **764** illumination may be expanded in a first dimension by the spaced apart facets of first waveguide aperture expander **778** to provide the first plurality of expanded image beams X7A**1**. A reflectivity of the first plurality of partially reflecting facets in first waveguide first aperture expander **778** may increase in a direction away from waveguide injection region WIR**71**, where the first waveguide first aperture expander **778** may have an initial facet with a lowest reflectivity and may terminate with a final facet **779** that may be a fully reflective mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**71** and, separate from this feature, may terminate with a final facet **779** that may or may not be a mirror.

[0080] Similarly, first waveguide second aperture expander **780** may include a second plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **783** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **783**. Illumination from the first plurality of expanded image beams X7A**1** may be received in the second direction and then reflected in a third direction toward first waveguide rear surface **784** by the second plurality of partially reflecting optical elements in first waveguide second aperture expander **780**. In this manner, illumination from first plurality of expanded image beams X7A**1** may be expanded in a second dimension by the spaced apart facets of first waveguide second aperture expander **780** to provide the second plurality of expanded image beams X7A**2**. The plurality of expanded image beams X7A**1** may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X7A**2**. Thus, the first waveguide first aperture expander **778** and the first waveguide second aperture expander **780** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one first propagated image beam **764** illumination as a first expanded output image beam **786** that may be emitted from first waveguide rear surface **784**. Similar to first waveguide first aperture expander **778**, a reflectivity of the second plurality of partially reflecting facets in first waveguide second aperture expander **780** may increase in a direction away from first waveguide first aperture expander **778**, where the first waveguide second aperture expander **780** may have an initial facet with a lowest reflectivity and a final facet that may be a mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from first waveguide first aperture expander **778** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0081] FIGS. **8**A-**8**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **8**A illustrates a front plan view of an optical system **802**, FIG. **8**B illustrates a first cross section of optical system **802** taken along an X-Z plane identified as cross section α (alpha), and FIG. **8**C illustrates a cross section of optical system **802** taken along a Y-Z plane identified as cross section β (beta), in accordance with various examples of the present disclosure.

[0082] According to an example, an optical device **802** may include an image pipe **860** integrated with a first waveguide **876** (Labeled as "A"). Optical device **802** may include a second waveguide **888** (Labeled as "B") that may be affixed to a rear surface of first waveguide **876**, and/or a portion of image pipe **860** may be affixed to a portion of first waveguide **876** using a low index of refraction (LRI) adhesive **806**, for example. Optical device **802** may also include a coupling assembly **820** that may be disposed at least partially between a portion of first waveguide **876** and second waveguide **888**. First waveguide **876** may have a first waveguide front surface **883** that is parallel with a first waveguide rear surface **884**. Second waveguide **888** may have a second waveguide front surface **895** that is parallel with a second waveguide rear surface **896**. In some examples, first waveguide **876** may directly receive a collimated image beam **810** (an "i" image beam) from a projecting optical device **132** to an image pipe input **862** of image pipe **860** and may be injected at an oblique angle relative to first waveguide major surfaces. In an example, first waveguide **876** may also include a first mirror **851** configured to receive the collimated image beam **810** and provide a reflected image beam **853** to image pipe input **862**. Similar to the description above, directly injected image beam **810** or reflected image beam **853** may be propagated within image pipe **860** as at least one first propagated image beam **864** to image pipe output **866**. Within image pipe **860**, the at least one first propagated image beam **864** may be received from a first direction and may be reflected in a second direction by a second mirror **855** to provide a first reflected at least one first propagated image beam **857** which may be further reflected by a third mirror **854** in a third direction (e.g., opposite to the first direction) to provide a second reflected at least one first propagated image beam **864** at image pipe output **866** that may be injected into first waveguide **876** at a waveguide injection region WIR**81**. In this manner, image pipe **860** may have multiple segments and mirrors to propagate an image beam around a portion of first waveguide **876** to a waveguide injection region WIR**81** at a distance from projecting optical device **132** and may enable injection of images (e.g., image beams) from previously unreached directions, for example.

[0083] Coupling assembly **820** may be positioned between a portion of second waveguide **888** and a portion of first waveguide **876** where collimated image beam **810** may be injected into a rear surface **896** of second waveguide **888**. Coupling assembly **820** may include a polarizing beam splitter **822** having a first side and a second side. Coupling assembly **820** may also include a half wave plate **830** having a first side and a second side. Polarizing beam splitter **822** first side may be positioned adjacent to a portion of second waveguide **888** and configured to receive a portion of collimated image beam **810** injected at second waveguide rear surface **896**. Polarizing beam splitter **822** may reflect a portion of collimated image beam **810** injected at second waveguide rear surface **896** having an S-polarization as a first output beam **812** (e.g., a "j" image beam) to be propagated within second waveguide **888** and to reflect from second waveguide front surface **895**. Polarizing beam splitter **822** may transmit a portion of collimated image beam **810** that escapes second waveguide front surface **895** having P-polarization directed to half wave plate **830** first side which may convert the incident portion of collimated image beam **810** having P-polarization to now having S-polarization emitted from half wave plate second side and injected to first waveguide **876** rear surface **884** as a second output beam **814** (e.g., a "k" image beam) to be propagated within first waveguide **876**.

[0084] First waveguide **876** (labeled as "A") may include a first waveguide first aperture expander **878** and a first waveguide second aperture expander **880** separated from each other by a first waveguide dividing region **882**. First waveguide first aperture expander **878** may include a first plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **883** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **883**. Illumination from the reflected at least one first propagated image beam **864** may be received in a first direction (e.g., along a central axis of first waveguide aperture expander **878**) and then reflected in a second direction and propagated within first waveguide **876** as a first waveguide first plurality of expanded image beams X**8**A**1** that may be directed to first waveguide second aperture expander **880**. In this manner, the reflected at least one first propagated image beam **864** illumination may be expanded in a first dimension by the spaced apart facets of first waveguide aperture expander **878** to provide the first plurality of expanded image beams X**8**A**1**. A reflectivity of the first plurality of partially reflecting facets in first waveguide first aperture expander **878** may increase in a direction away from waveguide injection region WIR**81**, where the first waveguide first aperture expander **878** may have an initial facet with a lowest reflectivity and may terminate with a final facet **879** that may be a fully reflective mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**81** and, separate from this feature, may terminate with a final facet **879** that may or may not be a mirror.

[0085] Similarly, first waveguide second aperture expander **880** may include a second plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **883** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **883**. Illumination from the first plurality of expanded image beams X**8**A**1** may be received in the second direction and then reflected in a third direction toward first waveguide rear surface **884** by the second plurality of partially reflecting optical elements in first waveguide second aperture expander **880**. In this manner, illumination from first plurality of expanded image beams X**8**A**1** may be expanded in a second dimension by the spaced apart facets of first waveguide second aperture expander **880** to provide the second plurality of expanded image beams X**8**A**2**. The plurality of expanded image beams X**8**A**1** may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X**8**A**2**. Thus, the first waveguide first aperture expander **878** and the first waveguide second aperture expander **880** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one first propagated image beam **864** illumination as a first expanded output image beam **886** that may be emitted from first waveguide rear surface **884**. Similar to first waveguide first aperture expander **878**, a reflectivity of the second plurality of partially reflecting facets in first waveguide second aperture expander **880** may increase in a direction away from first waveguide first aperture expander **878**, where the first waveguide second aperture expander **880** may have an initial facet with a lowest reflectivity and a final facet that may be a mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from first waveguide first aperture expander **878** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0086] Second waveguide **888** (labeled as "B") may include a second waveguide first aperture expander **890** and a second waveguide second aperture expander **892** separated from each other by a second waveguide dividing region **894**. Second waveguide first aperture expander **890** may include a third plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **895** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **895**. Illumination from the first output image beam **812** may be received in a fourth direction (e.g., along a central axis of the second waveguide aperture expander **890**) and then reflected in a fifth direction by the first plurality of partially reflecting optical elements in second waveguide first aperture expander **890** and conducted within second waveguide **888** as a second waveguide first plurality of expanded image beams X**8**B**1** that may be directed to second waveguide second aperture expander **892**. In this manner, the first output image beam **812** illumination may be expanded in a first dimension (e.g., a third dimension) by the spaced apart facets to provide the first plurality of expanded image beams X**8**B**1**. A reflectivity of the third plurality of partially reflecting facets in second waveguide first aperture expander **890** may increase in a direction away from a second waveguide injection region WIR**82**, where the second waveguide first aperture expander **890** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a mirror. Alternatively, a reflectivity of the third plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**82** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0087] Similarly, second waveguide second aperture expander **892** may include a fourth plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of second waveguide front surface **895** and a plane (e.g., an X-Z plane) that is perpendicular to second waveguide front surface **895**. Illumination from the third plurality of expanded image beams X**8**B**1** may be received in the fifth direction and then reflected in a sixth direction toward second waveguide rear surface **896** by the fourth plurality of partially reflecting optical elements in second waveguide second aperture expander **892**. In this manner, illumination from third plurality of expanded image beams X**8**B**1** may be expanded in a second dimension (e.g., a fourth dimension) by the spaced apart facets of second waveguide second aperture expander **892** to provide the second plurality of expanded image beams X**8**B**2**. In this manner, the plurality of expanded image beams X**8**B**1** may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X**8**B**2**. Thus, the second waveguide first aperture expander **890** and the second waveguide second aperture expander **892** may cooperate to provide a two-dimensional (2D) expansion of the first output image beam **812** illumination as a second expanded output image beam **898** that may be emitted from second waveguide rear surface **896**. Similar to second waveguide first aperture expander **890**, a reflectivity of the fourth plurality of partially reflecting facets in second waveguide second aperture expander **892** may increase in a direction away from second waveguide first aperture expander **890**, where the second waveguide second aperture expander **892** may have an initial facet with a lowest reflectivity and a final facet (e.g., a terminal facet) that is a mirror. Alternatively, a reflectivity of the fourth plurality of partially reflecting facets may be constant in a direction away from second waveguide first aperture expander **890** and, separate from this feature, may terminate with a final facet that may or may not be a mirror. According to an example, first waveguide first aperture expander **878** and second waveguide first aperture expander **890** may be oriented parallel to each other. Other arrangements are also possible, where both first waveguide **876** and second waveguide **888** may be rotated.

[0088] As described above, second waveguide **888** may be configured to receive the first output image beam **812** and emit a second expanded output image beam **898** from second waveguide rear surface **896**, and first waveguide **876** may be configured to receive the second output image beam **814** and emit a first expanded output image beam **886** from first waveguide rear surface **884**. It is noted that first expanded output image beam **886** and second expanded image beam **898** are coincident and expanded separately from different directions, and both first expanded output image beam **886** and second expanded image beam **898** may be emitted toward an eye of a user to convey optical information. Hence, in this configuration first waveguide **876** with one embedded image pipe **860** along with an overlapping second waveguide **888** may cooperate to effectively double a field of view (FoV) provided by optical device **802** compared with a single waveguide example.

[0089] According to an example, coupling assembly **820** may also include an active half wave plate liquid crystal element (AHWP) **848** configured to receive the collimated image beam **810** and provide a transformed image beam **850**. Active half wave plate liquid crystal element **848** may be an active optical element controlled by signals from controller **114** to selectively change polarity of at least a portion of collimated image beam **810** and provide transformed image beam **850**, such as changing from an S-polarization to a P-polarization when activated, for example. A liquid crystal half wave plate may be a two-dimensional (2D) array of cells filled with liquid crystals that may twist and align in response to a control voltage. In this manner, active half wave plate liquid crystal element **848** may provide variable retardance (e.g., variable delay) by selectively tilting various liquid crystal molecules in the active half wave plate liquid crystal element **848**, for example. The angle of tilt may be rapidly changed on the order of milliseconds. Similar to other examples described above, optical device **802** may be practiced with or without active half wave plate liquid crystal element **848**.

[0090] FIGS. **9**A-**9**C illustrate details regarding an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **9**A illustrates a front plan view of an optical system **902**, FIG. **9**B illustrates a first cross section of an image pipe **960** taken along an X-Z plane illustrating a homogenizing layer **963** having a first orientation, and FIG. **9**C illustrates a first cross section of an image pipe **960** taken along an X-Z plane illustrating a homogenizing layer **965** having a second orientation perpendicular to the first orientation, in accordance with various examples of the present disclosure.

[0091] According to an example, an optical device **902** may include an image pipe **960** integrated with a first waveguide **976** (Labeled as "A"). A portion of image pipe **960** may be affixed to a portion of first waveguide **976** using a low index of refraction (LRI) adhesive **906**, for example. First waveguide **976** may have a first waveguide front surface **983** that is parallel with a first waveguide rear surface **984**. In some examples, first waveguide **976** may directly receive a collimated image beam **910** (an "i" image beam) from a projecting optical device **132** (not shown) to an image pipe input **962** of image pipe **960**. Similar to the description above, directly injected image beam **910** may be propagated within image pipe **960** as at least one first propagated image beam **964** to image pipe output **966**. Within image pipe **960**, the at least one first propagated image beam **964** may be received from a first direction and may be reflected in a second direction by a mirror **955** to provide a reflected at least one propagated image beam **957** at image pipe output **966** that may be injected into first waveguide **976** at a waveguide injection region WIR**91**. In this manner, image pipe **960** may propagate an input image beam to a waveguide injection region WIR**91** at a distance from an image source, for example. FIG. **9**B illustrates a first cross section of an image pipe **960** taken along an X-Z plane illustrating a homogenizing layer **963** having a first orientation, and FIG. **9**C illustrates a first cross section of an image pipe **960** taken along an X-Z plane illustrating a homogenizing layer **965** having a second orientation perpendicular to the first orientation, in accordance with various examples of the present disclosure. Homogenizing layer **963** and/or homogenizing layer **965** may be formed as a coating layer or film along a length of image pipe **960** and disposed within image pipe **960**. Homogenizing layer **963** and/or homogenizing layer **965** may improve illumination uniformity prior to expansion resulting in a more evenly illuminated and expanded image.

[0092] First waveguide **976** (labeled as "A") may include a first waveguide first aperture expander **978** and a first waveguide second aperture expander **980** separated from each other by a first waveguide dividing region **982**. First waveguide first aperture expander **978** may include a first plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **983** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **983**. Illumination from the reflected at least one first propagated image beam **964** may be received in a first direction (e.g., along a central axis of first waveguide aperture expander **978**) and then reflected in a second direction and propagated within first waveguide **976** as a first waveguide first plurality of expanded image beams X**9**A**1** that may be directed to first waveguide second aperture expander **980**. In this manner, the reflected at least one first propagated image beam **964** illumination may be expanded in a first dimension by the spaced apart facets of first waveguide aperture expander **978** to provide the first plurality of expanded image beams X**9**A**1**. A reflectivity of the first plurality of partially reflecting facets in first waveguide first aperture expander **978** may increase in a direction away from waveguide injection region WIR**91**, where the first waveguide first aperture expander **978** may have an initial facet with a lowest reflectivity and may terminate with a final facet that may be a fully reflective mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from waveguide region WIR**91** and, separate from this feature, may terminate with a final facet that may or may not be a mirror.

[0093] Similarly, first waveguide second aperture expander **980** may include a second plurality of planar, mutually-parallel and partially reflecting optical elements (e.g., facets) spaced apart from each other which may be inclined at an angle that may be one of oblique relative to at least one of first waveguide front surface **983** and a plane (e.g., an X-Z plane) that is perpendicular to first waveguide front surface **983**. Illumination from the first plurality of expanded image beams X**9**A**1** may be received in the second direction and then reflected in a third direction toward first waveguide rear surface **984** by the second plurality of partially reflecting optical elements in first waveguide second aperture expander **980**. In this manner, illumination from first plurality of expanded image beams X**9**A**1** may be expanded in a second dimension by the spaced apart facets of first waveguide second aperture expander **980** to provide the second plurality of expanded image beams X**9**A**2**. The plurality of expanded image beams X**9**A**1** may be expanded in a second dimension that is different from the first dimension to provide a second plurality of expanded image beams X**9**A**2**. Thus, the first waveguide first aperture expander **978** and the first waveguide second aperture expander **980** may cooperate to provide a two-dimensional (2D) expansion of the reflected at least one first propagated image beam **964** illumination as a first expanded output image beam **986** that may be emitted from first waveguide rear surface **984**. Similar to first waveguide first aperture expander **978**, a reflectivity of the second plurality of partially reflecting facets in first waveguide second aperture expander **980** may increase in a direction away from first waveguide first aperture expander **978**, where the first waveguide second aperture expander **980** may have an initial facet with a lowest reflectivity and a final facet that may be a mirror. Alternatively, a reflectivity of the first plurality of partially reflecting facets may be constant in a direction away from first waveguide first aperture expander **978** and, separate from this feature, may terminate with a final facet that may or may not be a mirror. The homogenizing layer **963** having a first orientation illustrated in FIG. **9**B and the homogenizing layer **965** having a second orientation illustrated in FIG. **9**C may enable a reduced input aperture in some examples.

[0094] FIGS. **10**A-**10**H illustrate details regarding various configurations of optical systems, in accordance with various examples of the present disclosure. Further, the optical systems illustrated in FIGS. **7**A-**7**C, FIGS. **8**A-**8**C, and FIGS. **9**A-**9**C may be suitably combined with any of the optical systems illustrated in FIGS. **10**A-**10**H. In this manner, each of the first waveguide and second waveguide illustrated in FIGS. **10**A-**10**H may be either or both implemented as a single waveguide or a double waveguide, as described. Also, the orientation of some elements in various illustrations may be modified, swapped, rotated, reflected, or moved relative to similar elements in corresponding illustrations while retaining the same functions. It is intended that each of the features illustrated with the various examples may be combined in any manner that is consistent with the present disclosure.

[0095] FIG. **10**A illustrates a front plan view of an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **10**A illustrates an optical system that may be similar in some ways to the optical systems illustrated in FIG. **3**A and FIG. **4**A. In this manner, FIG. **10**B may illustrate an optical system that may be considered as a modified version of the optical system illustrated in FIG. **10**A. In FIG. **10**A and elsewhere, an eye (**1007**, **1008**) and a nose **1009** of a user may be illustrated to provide a reference for how optical system **1002** may be worn on a head of a user and used to provide optical information, as described. For reference, a user right side **1000** and a user left side **1001** may indicate, from a user's perspective, a relative position of elements for optical system **1002**, and others. A frame **1048** may be configured to support various elements of optical system **1002** such as a projecting optical device (POD), the coupling assembly with various passive and/or active elements, the one or more image pipes, the first waveguide and the second waveguide, and the like. Frame **1048** may be configured to conceal the one or more image pipes or other elements within a portion of the frame. In this manner, the one or more image pipes, will not be visible after optical system **1002** is assembled. FIG. **10**C illustrates a front plan view of an optical system, in accordance with various examples of the present disclosure. Similarly, FIG. **10**D may illustrate an optical system that may be considered as a modified version of the optical system illustrated in FIG. **10**C.

[0096] Similarly, FIG. **10**E illustrates a front plan view of an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **10**E illustrates an optical system that may be similar in some ways to the optical systems illustrated in FIG. **5**A. In some ways, FIG. **10**F may illustrate an optical system that may considered as a modified version of the optical systems illustrated in FIG. **10**E.

[0097] Finally, FIG. **10**H illustrates a front plan view of an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **10**H illustrates an optical system that may be similar in some ways to the optical systems illustrated in FIG. **6**A. FIG. **10**G illustrates a front plan view of an optical system, in accordance with various examples of the present disclosure. In particular, FIG. **10**G illustrates an optical system that may also be similar in some ways to a modified version of the optical systems illustrated in FIG. **6**A. In the example of FIG. **10**G, longer image pipes may be used relative to the shorter image pipes (e.g., I.P.) shown in FIG. **10**H so that a first injection point for a first image beam to a first waveguide may be located farther to a user right side and a second injection point for a second image beam to a second waveguide may be located farter to a user left side compared with corresponding injection points for the image beams illustrated in FIG. **10**H or FIG. **6**A, for example.

[0098] 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.

[0099] 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.

What is claimed is:

1. An optical device comprising:

a coupling assembly configured to receive a collimated image beam and provide a first output image beam and a second output image beam;

an image pipe configured to receive the first output image beam at an image pipe input and provide at least one propagated image beam at an image pipe output;

a first waveguide having a first waveguide rear surface, the first waveguide configured to receive the second output image beam and emit a first expanded output image beam from the first waveguide rear surface; and

a second waveguide having a second waveguide rear surface, the second waveguide configured to receive the at least one propagated image beam and emit a second expanded output image beam from the second waveguide rear surface.

2. The optical device of claim **1**, wherein the coupling assembly further comprises:

a semitransparent mirror having a semitransparent mirror first surface and a semitransparent mirror second surface opposite the semitransparent mirror first surface, the semitransparent mirror first surface configured to receive the collimated image beam and provide the first output image beam reflected from the semitransparent mirror first surface and provide the second output image beam emitted from the semitransparent mirror second surface.

3. The optical device of claim **2**,

wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and

wherein the second waveguide comprises a mirror configured to receive the at least one propagated image beam and provide a reflected at least one propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

4. The optical device of claim **3**, further comprising:

an image projector configured to provide the collimated image beam based on a digital image, wherein the collimated image beam is collimated to infinity, and wherein the projector includes a liquid crystal on silicon display.

5. An optical system comprising:

an image projector configured to provide a collimated image beam based on a digital image;

a coupling assembly configured to receive the collimated image beam and provide a first output image beam and a second output image beam;

an image pipe configured to receive the first output image beam at an image pipe input and provide at least one propagated image beam at an image pipe output;

a first waveguide having a first waveguide rear surface, the first waveguide configured to receive the second output image beam and emit a first expanded output image beam from the first waveguide rear surface; and

a second waveguide having a second waveguide rear surface, the second waveguide configured to receive the at least one propagated image beam and emit a second expanded output image beam from the second waveguide rear surface.

6. The optical system of claim **5**, wherein at least one of:

the collimated image beam is collimated to infinity;

the projector includes one of a liquid crystal display, a liquid crystal on silicon display, an organic light emitting diode display, a micro light emitting diode display, and a laser display;

the image pipe includes at least one of a glass material, an acrylic material, and a polycarbonate material;

a portion of the first waveguide is affixed to a portion of the image pipe with a layer of low refractive index adhesive; and

the image pipe is an elongated transparent member having a first end and a second end with a rectangular cross section and orthogonal walls, the image pipe configured to receive at least one input image beam and provide four replicated output image beams based on the at least one input image beam.

7. The optical system of claim **5**,

wherein the coupling assembly comprises a semitransparent mirror having a semitransparent mirror first surface and a semitransparent mirror second surface opposite the semitransparent mirror first surface, the semitransparent mirror first surface configured to receive the collimated image beam and provide the first output image beam reflected from the semitransparent mirror first surface and to provide the second output image beam emitted from the semitransparent mirror second surface; and

wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and

wherein the second waveguide comprises a mirror configured to receive the at least one propagated image beam and provide a reflected at least one propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

8. The optical system of claim **5**, wherein the coupling assembly comprises:

a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the collimated image beam and provide the first output image beam from the polarizing beam splitter first side and provide a transmitted image beam from the polarizing beam splitter second side; and

a half wave plate having a half wave plate first side and a half wave plate second side, the half wave plate being configured to receive the transmitted image beam at the half wave plate first side and provide the second output image beam from the half wave plate second side.

9. The optical system of claim **8**,

wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and

wherein the second waveguide comprises a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

10. The optical system of claim **5**, wherein the coupling assembly further comprises:

an active half wave plate liquid crystal element configured to receive the collimated image beam and provide a transformed image beam;

a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the transformed image beam and provide the first output image beam from the polarizing beam splitter first side and provide a transmitted image beam from the polarizing beam splitter second side; and

a half wave plate having a half wave plate first side and a half wave plate second side, the half wave plate being configured to receive the transmitted image beam on the half wave plate first side and provide the second output image beam from the half wave plate second side.

11. The optical system of claim **10**,

wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and

wherein the second waveguide comprises a mirror configured to receive the at least one propagated image beam and provide a reflected at least one propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

12. The optical system of claim **10**,

wherein the first waveguide comprises a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the second output image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and

wherein the second waveguide comprises a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the at least one propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

13. The optical system of claim **10**, wherein the image pipe is a first image pipe and wherein the first waveguide includes a first waveguide front surface that is opposite the first waveguide rear surface, the optical system further comprising:

a third waveguide having a third waveguide rear surface, the third waveguide configured to receive the second output image beam and emit a third expanded output image beam from the third waveguide rear surface, the third waveguide rear surface being affixed to the first waveguide front surface, the third waveguide comprising:

a second image pipe configured to receive the second output image beam and provide at least one propagated third image beam at a third image pipe output;

a third waveguide first aperture expander, the third waveguide first aperture expander configured to expand the at least one propagated third image beam and provide a third waveguide first plurality of expanded image beams; and

a third waveguide second aperture expander configured to expand the first plurality of expanded image beams and provide a third waveguide second plurality of expanded image beams to be emitted as the third expanded output image beam, the second image pipe configured to surround at least a portion of the third waveguide second aperture expander.

14. The optical system of claim **5**, further comprising:

a frame configured to support the image projector, the coupling assembly, the image pipe, the first waveguide and the second waveguide, the frame being configured to conceal the image pipe within a portion of the frame.

15. An optical system comprising:

an image projector configured to provide a collimated image beam based on a digital image;

a coupling assembly configured to receive the collimated image beam and provide a first output image beam and a second output image beam;

a first image pipe configured to receive the first output image beam at a first image pipe input and provide an at least one first propagated image beam at a first image pipe output;

a second image pipe configured to receive the second output image beam at a second image pipe input and provide an at least one second propagated image beam at a second image pipe output;

a first waveguide having a first waveguide rear surface, the first waveguide configured to receive the at least one second propagated image beam and emit a first expanded output image beam from the first waveguide rear surface; and

a second waveguide having a second waveguide rear surface, the second waveguide configured to receive the at least one first propagated image beam and emit a second expanded output image beam from the second waveguide rear surface.

16. The optical system of claim **15**, wherein the coupling assembly comprises:

an active half wave plate liquid crystal element configured to receive the collimated image beam and provide a transformed image beam;

a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the transformed image beam and provide the second output image beam from the polarizing beam splitter first side and provide a transmitted image beam from the polarizing beam splitter second side;

a quarter wave plate having a quarter wave plate first side and a quarter wave plate second side, the quarter wave plate being configured to receive the transmitted image beam on the quarter wave plate first side and provide a converted image beam from the quarter wave plate second side; and

a mirror having a reflective mirror surface configured to receive the converted image beam and provide a reflected image beam, the quarter wave plate configured to receive the reflected image beam on the quarter wave plate second side and provide a second converted image beam from the quarter wave plate first side, the polarizing beam splitter configured to receive the second converted image beam on the polarizing beam splitter second side and provide the first output image beam.

17. The optical system of claim **16**,

wherein the first waveguide comprises a first mirror configured to receive the at least one second propagated image beam and provide a reflected at least one second propagated image beam, the first waveguide further comprising a first waveguide first aperture expander and a first waveguide second aperture expander, the first waveguide first aperture expander being configured to expand the reflected at least one second propagated image beam and provide a first waveguide first plurality of expanded image beams directed to the first waveguide second aperture expander configured to expand the first waveguide first plurality of expanded image beams and provide a first waveguide second plurality of expanded image beams to be emitted as the first expanded output image beam; and

wherein the second waveguide comprises a second mirror configured to receive the at least one first propagated image beam and provide a reflected at least one first propagated image beam, the second waveguide further comprising a second waveguide first aperture expander and a second waveguide second aperture expander, the second waveguide first aperture expander being configured to expand the reflected at least one first propagated image beam and provide a second waveguide first plurality of expanded image beams directed to the second waveguide second aperture expander configured to expand the second waveguide first plurality of expanded image beams and provide a second waveguide second plurality of expanded image beams to be emitted as the second expanded output image beam.

18. The optical system of claim **15**, wherein the first waveguide includes a first waveguide front surface that is opposite the first waveguide rear surface, the optical system further comprising:

a third waveguide having a third waveguide rear surface, the third waveguide configured to receive the at least one second propagated image beam and emit a third expanded output image beam from the third waveguide rear surface, the third waveguide rear surface being affixed to the first waveguide front surface, the third waveguide comprising:

a third image pipe configured receive the at least one second propagated image beam and provide an at least one propagated third image beam at a third image pipe output;

a third waveguide first aperture expander, the third waveguide first aperture expander configured to expand the at least one propagated third image beam and provide a third waveguide first plurality of expanded image beams; and

a third waveguide second aperture expander configured to expand the first plurality of expanded image beams and provide a third waveguide second plurality of expanded image beams to be emitted as the third expanded output image beam, the second image pipe configured to surround at least a portion of the third waveguide second aperture expander, the second image pipe having a homogenizing layer.

19. The optical system of claim **18**, wherein the second waveguide includes a second waveguide front surface that is opposite the second waveguide rear surface, the optical system further comprising:

a polarizing beam splitter having a polarizing beam splitter first side and a polarizing beam splitter second side opposite the polarizing beam splitter first side, the polarizing beam splitter first side being configured to receive the at least one first propagated image beam and provide a second transmitted image beam from the polarizing beam splitter second side;

a half wave plate having a half wave plate first side and a half wave plate second side, the half wave plate being configured to receive the second transmitted image beam on the half wave plate first side and provide a second converted image beam from the half wave plate second side;

a fourth waveguide having a fourth waveguide rear surface, the fourth waveguide configured to receive the second converted image beam and emit a fourth expanded output image beam from the fourth waveguide rear surface, the fourth waveguide rear surface being affixed to the second waveguide front surface, the fourth waveguide comprising:

a fourth image pipe configured to receive the second converted image beam and provide an at least one propagated fourth image beam at a fourth image pipe output;

a fourth waveguide first aperture expander, the fourth waveguide first aperture expander configured to expand the at least one propagated first image beam and provide a fourth waveguide first plurality of expanded image beams; and

a fourth waveguide second aperture expander configured to expand the fourth plurality of expanded image beams and provide a fourth waveguide second plurality of expanded image beams to be emitted as the fourth expanded output image beam, the fourth image pipe configured to surround at least a portion of the fourth waveguide second aperture expander, the fourth image pipe including a homogenizing layer.

20. The optical system of claim **15**, further comprising:

a frame configured to support the image projector, the coupling assembly, the first image pipe, the second image pipe, the first waveguide and the second waveguide, the frame being configured to conceal the first image pipe and the second image pipe within a portion of the frame.

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