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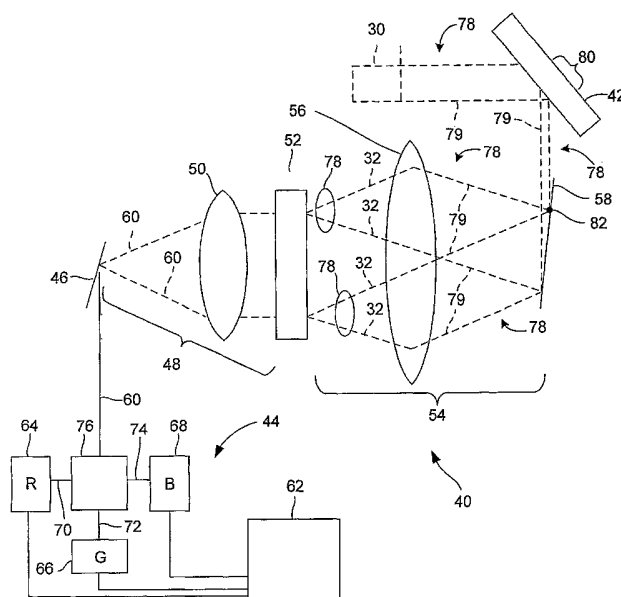
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(54) Title: SCANNED-BEAM HEADS-UP DISPLAY AND RELATED SYSTEMS AND METHODS



(57) Abstract: A heads-up display that includes a scanner (46) and a projection assembly (54). The scanner generates an image by sweeping a beam of electromagnetic energy, and the projection assembly directs the image into a predetermined viewing space having a region with a substantially uniform intensity profile. The device further comprises an exit pupil expander (52). Such a heads-up display can often be made smaller than a conventional heads-up display, and can often generate an image having a higher quality than an image generate by a conventional display. Furthermore, one can often calibrate and recalibrate such a display without physically modifying or replacing a component of the display or of a vehicle incorporating the display.



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SCANNED-BEAM HEADS-UP DISPLAY AND RELATED SYSTEMS AND METHODS

CLAIM OF PRIORITY

[1] This application claims priority to U.S. Provisional Application Serial
5 No. 60/541,619 filed on February 4, 2004, and U.S. Provisional Application Serial
No. 60/565,059 filed on April 23, 2004, both of which are incorporated by
reference.

BACKGROUND OF THE INVENTION

[2] Referring to **FIG. 1**, a heads-up display **10** typically generates a
10 virtual image of one or more gauges, *e.g.*, a speedometer and an odometer (not
shown), for viewing by an operator **12** of a vehicle such as an automobile **14**. The
term "heads up" indicates that the operator **12** need not lower his gaze to a
dashboard **16** to view the gauges. That is, the operator **12** can keep his head up
and his "eyes on the road" while viewing the gauges. Therefore, the display **10** is
15 an added convenience that also increases the level of safety with which the
operator **12** can operate the vehicle **14**.

[3] In operation, the heads-up display **10** generates and projects the
virtual image of the one or more gauges (not shown) onto a windshield, *i.e.*, a
wind screen **18**, which reflects the image into the eyes **20** of the operator **12** such
20 that the image appears within the operator's field of view (FOV), sometimes
appearing to be at some apparent distance beyond the wind screen. For
example, the display **10** may include a light-emitting-diode (LED), liquid crystal
(LCD), vacuum fluorescent, or other display technology (not shown) for
generating the image, and an optical train (not shown in **FIG. 1**) for projecting the
25 image onto the wind screen **18**.

[4] Typically, the operator **12** is best able to view the virtual image while
his eyes **20** are within a three-dimensional viewing space **22**, which is sometimes
called an eye box. Although the dimensions (*e.g.*, height, width, and/or depth) of
the viewing space **22** are typically fixed, they are typically sufficient to
30 accommodate the anticipated ranges of up-and-down, side-to-side, and
front-to-back movements of the operator's head **20** while the operator is operating

the automobile **14**. Furthermore, because the range of operator heights is relatively large (e.g., 5 feet tall – 7 feet tall), the display **10** may allow the operator **12** to adjust the vertical position of the viewing space **22** so as to align the viewing space with the operator's eyes **20**.

5 **[5]** Unfortunately, the typical heads-up display **10** may have several shortcomings. For example, the display **10** may be relatively bulky, and may consume a relatively large amount of power. Furthermore, the quality of the virtual image within the viewing space **22** may be poor. Moreover, because each wind screen **18**, even for the same model car, may be slightly different than every
10 other wind screen, the procedure for calibrating the display **10** for each new vehicle may be relatively complex, and may include physically modifying or replacing one or more parts of the display, or perhaps either replacing the entire heads-up display or wind screen. Furthermore, if one ever needs to repair or replace the windscreen, the need to recalibrate the display **10** by modifying or
15 replacing a part or all of the display may significantly increase the time and expense required for an otherwise ordinary repair.

SUMMARY OF THE INVENTION

[6] One aspect of the invention is a heads-up display that includes a scanner assembly and a projection assembly. The scanner assembly generates
20 an image by sweeping a beam of electromagnetic energy, and the projection assembly directs the image into a predetermined viewing space having a region with a substantially uniform intensity profile.

[7] Such a heads-up display can often be made smaller than a conventional heads-up display, and can often generate an image having a higher
25 quality than an image generated by a conventional display. Furthermore, one can often calibrate and recalibrate such a display without physically modifying or replacing a component of the display or of a vehicle incorporating the display.

BRIEF DESCRIPTION OF THE DRAWINGS

[8] The foregoing aspects and many of the attendant advantages of this
30 invention will become more readily appreciated as the same become better

understood by reference to the following non-limiting detailed description, when taken in conjunction with the accompanying drawings, wherein:

- [9] **FIG. 1** is a side view with portions broken away of an operator within a vehicle that includes a conventional heads-up display.
- 5 [10] **FIG. 2** is an isometric view of a heads-up-display viewing space (eye box) according to an embodiment of the invention.
- [11] **FIG. 3** is a diagram of a heads-up display system that can project an image into the viewing space of **FIG. 2** according to an embodiment of the invention.
- 10 [12] **FIG. 4** is a diagram of a three color beam generator of **FIG. 3** according to an embodiment of the invention.
- [13] **FIG. 5** is a plot of the Gaussian intensity profile of the beams within the beam generator of **FIG. 4** laid over a plot of the top-hat (uniform) intensity profile of the scan beam generated by the beam generator of **FIG. 4** according to an embodiment of the invention.
- 15 [14] **FIG. 6** is a diagram of a three color beam generator of **FIG. 3** according to another embodiment of the invention.
- [15] **FIG. 7** is a side view of the exit-pupil expander of **FIG. 3** according to an embodiment of the invention.
- 20 [16] **FIG. 8** is a plan view of a hexagonally arranged microlens array of **FIG. 7** according to an embodiment of the invention.
- [17] **FIG. 9A** is a two-dimensional plot of a beam-envelope intensity profile generated by the exit-pupil expander of **FIG. 7** according to an embodiment of the invention.
- 25 [18] **FIG. 9B** is a two-dimensional plot of a beamlet intensity profile generated by the heads-up display **40** of **FIG. 3** for a scanned beam having a Gaussian intensity profile according to an embodiment of the invention.
- [19] **FIG. 9C** is a two-dimensional plot of the beam intensity profile resulting from the combination of the beam-envelope intensity profile of **FIG. 9A**

and the beamlet intensity profile of **FIG. 9B** according to an embodiment of the invention.

[20] **FIGS. 10A and 10B** illustrate intensity non-uniformities within the viewing space of **FIG. 2** caused by the resulting beam intensity profile of **FIG. 9C**
5 according to an embodiment of the invention.

[21] **FIG. 11A** is a two-dimensional plot of a beamlet intensity profile generated by the heads-up display **40** of **FIG. 3** for a scan beam having a top-hat intensity profile according to an embodiment of the invention.

[22] **FIG. 11B** is a two-dimensional plot of a uniform beam intensity
10 profile resulting from the combination of the beam-envelope intensity envelope of **FIG. 9A** and the beamlet intensity profile of **FIG. 11B** according to an embodiment of the invention.

[23] **FIG. 12** illustrates a simplified or ideal intensity uniformity within the viewing-space of **FIG. 2** caused by the uniform beam intensity profile of **FIG. 11B**
15 according to an embodiment of the invention.

[24] **FIG. 13** is a plan view of one of the microlens arrays of **FIG. 7** according to another embodiment of the invention.

[25] **FIG. 14** is a side view of the exit-pupil expander of **FIG. 3** according to another embodiment of the invention.

20 [26] **FIG. 15** is an isometric view of the exit-pupil expander of **FIG. 3** according to another embodiment of the invention.

[27] **FIG. 16** is an isometric view of the exit-pupil expander of **FIG. 3** according to another embodiment of the invention.

[28] **FIG. 17** is a side view of the exit-pupil expander of **FIG. 3** according
25 to another embodiment of the invention.

[29] **FIG. 18** is a side view of the exit-pupil expander of **FIG. 3** according to another embodiment of the invention.

[30] **FIG. 19** is an isometric view of the surface topography of the exit-pupil expander of **FIG. 3** according to another embodiment of the invention.

[31] **FIG. 20** is an isometric view of a portion of the projection assembly of **FIG. 3** according to an embodiment of the invention.

[32] **FIG. 21** is a diagram of a distorted virtual image generated by the heads-up display of **FIG. 3** when the display is not calibrated to the wind screen.

5 [33] **FIG. 22** is a diagram of an undistorted virtual image generated by the heads-up display of **FIG. 3** after the display is calibrated to the wind screen according to an embodiment of the invention.

DETAILED DESCRIPTION

[34] The following discussion is presented to enable a person skilled in the art to make and use the invention. The general principles described herein may be applied to embodiments and applications other than those detailed below without departing from the spirit and scope of the present invention. Therefore the present invention is not intended to be limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features disclosed or suggested herein.

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The Viewing Space

[35] **FIG. 2** is an isometric view of a viewing space **30** according to an embodiment of the invention. Generally, it is desired that a heads-up display, such as the scanned-beam heads-up display discussed below in conjunction with **FIGS. 3-22**, generate the viewing space **30** such that parameters of the viewing space are within respective predetermined ranges that allow a virtual image to have an acceptable and substantially uniform quality regardless of the position of the operator's eyes within the viewing space. Therefore, some of these viewing-space parameters, as well as desired values for these parameters, are discussed below in conjunction with **FIG. 2**. Following the discussion of the viewing space parameters is a discussion, in conjunction with **FIGS. 3-22**, of a heads-up display that can achieve desired parameter values.

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[36] Still referring to **FIG. 2**, the viewing space **30** has a height h (y dimension), a width w (x dimension), and a depth d (z dimension), and the virtual image perceived when the eye is within the viewing space **30** is formed by diffraction orders, *i.e.*, beamlets **32**, which, at any point in time, each carry the

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same pixel of the virtual image — for clarity, only four beamlets **32a-32d** are shown. Therefore, as long as the operator's eyes (not shown in **FIG. 2**) are capturing the light energy of at least one of the beamlets **32**, the operator will perceive the pixel of the image. During the generation of the center pixel of the image, the beamlets **32** are positioned approximately parallel to the z axis as shown in **FIG. 2**. During the generation of other pixels, the beamlets **32** are canted (canting not shown in **FIG. 2**) at slight angles relative to the z axis. That is, as the heads-up display (not shown in **FIG. 2**) scans the image pixel by pixel and line by line, the beamlets **32** effectively "pivot" up/down and left/right, within the FOV, from the nominal beamlet angle of the center-pixel position; it is this "pivoting" that causes one or more of the beamlets **32** to be scanned onto the retinas (not shown) of the operator's eyes. The location at which the beamlets **32** "pivot" is a cross section **34** that is coplanar with the x - y plane and that is located in the middle ($d/2$) of the viewing space **30** in the z dimension. Therefore, as a result of this "pivoting," the height h and the width w of the viewing space **30** (which includes beamlets from all pixels within the FOV) actually changes slightly as one moves out from the cross section **34** in either direction in the z dimension. But because this expansion is slight, describing the viewing space **30** as having constant values of h and w along the entire depth d is a good approximation.

[37] Parameters of the viewing space **30** that affect the virtual image quality and uniformity include the aperture, the expanded-beam intensity profile, and the fill factor. The aperture of the viewing space **30** is of the same shape as that of the cross section **34**. The expanded-beam intensity profile, which is discussed below in conjunction with **FIGS. 3** and **7-12**, is a plot of the relative expanded-beam intensity at each location within the viewing space, and the fill factor is a measure of the spacing S between adjacent beamlets **32**. Ideally, the aperture of the viewing space **30** should match the x - y area within which an operator is likely to move his head, the expanded beam-intensity profile should be uniform throughout the viewing space, and the fill factor should be such that there are no visible gaps between adjacent beamlets **32**.

[38] The aperture of the viewing space **30** has an elongated hexagonal shape, which has been found to closely mimic the typical x - y area within which

the operator may move his eyes while operating a vehicle (neither operator, eyes, nor vehicle shown in **FIG. 2**). The pattern of the beamlets **32**, which is further discussed below in conjunction with **FIGS. 7-8**, defines the aperture of the viewing space **30**. In this example, the beamlets **32** are in a hexagonal pattern having a compressed height **h** and an elongated width **w** as compared to a symmetrical hexagon — **h** is less than, *i.e.*, is compressed relative to, **w** because for the exemplary application the horizontal range within which an operator might move his eyes while operating the vehicle is greater than the vertical range within which the operator typically moves his eyes. Consequently, the aperture of the viewing space **30** has a shape that accommodates relatively greater horizontal movement and relatively less vertical movement. In one example, the viewing space **30** has a height **h** $\approx$ 150 millimeters, a width **w** $\approx$ 200 millimeters, and a depth **d** $\approx$ 400 millimeters. Other applications may be characterized by a range of operator eye positions that has a different shape. The aperture of the viewing space **30** may be similarly modified to accommodate such a different shape.

[39] Still referring to **FIG. 2**, the expanded-beam intensity (*i.e.*, brightness) profile within the viewing space **30** is substantially uniform. That is, the brightness of the image is substantially the same regardless of the position of the operator's eyes (not shown in **FIG. 2**) within the viewing space **30**. A relatively uniform expanded-beam intensity profile allows the operator move his eyes within the viewing space **30** without perceiving, and thus being distracted by, a noticeable change in the image intensity. There are two primary factors that determine the expanded-beam intensity profile within the viewing space **30**: the intensity profile of the beam envelope (not shown in **FIG. 2**), and the intensity profile of the beamlets **32**. For many embodiments, the beamlets each have substantially the same intensity profile. As further discussed below in conjunction with **FIGS. 9A-12**, as long as the intensity profile of the beam envelope and the intensity profile of the beamlets **32** are both substantially uniform, then the expanded-beam intensity profile within the viewing space **30** is also substantially uniform. In one example, the brightest region of the expanded-beam intensity profile within the viewing space **30** is approximately 11% brighter than the dimmest region of the beam intensity profile within the viewing space. That is,

$$(I_{\text{brightest}} - I_{\text{dimmest}}) / (I_{\text{brightest}} + I_{\text{dimmest}}) \leq \sim 11\%.$$

[40] The fill factor of the viewing space **30** is high enough to insure that an operator's eye (not shown in **FIG. 2**), while within the viewing space, captures at least one beamlet **32**, and thus perceives the virtual image regardless of the eye's position within the viewing space. That is, there are no "holes" in the viewing space **30** where an operator can "lose" the image. The fill factor can range from 0% where the beamlets **32** do not exist, *i.e.*, have a zero-diameter aperture, to 100% where the beamlets **32** are contiguous at all points of their respective peripheries such that there is no "empty" space between the beamlets, to greater than 100% where the beamlets **32** overlap. Although it is possible for the beamlets to overlap, it is assumed for purposes of this discussion that no such overlapping occurs. The aperture of the beamlets **32** controls the maximum fill factor of the viewing space **30**. For example, with beamlets having a circular aperture, the maximum fill factor when the beamlets are packed with their diameters just tangent to one another is less than 100% because of the interstitial spaces between the circles. If beamlets **32** have a hexagonal shape, the beamlets may be closely packed within the viewing space **30** and have a fill factor of 100% without overlapping. Similarly, flattened hexagonal, square, rectangular, parallelogram, etc. beamlet shapes may be closely packed without overlapping. To ensure that an operator's eye receives at least one beamlet **32**, the spacing **S** between the sides of adjacent beamlets is less than the smallest diameter of the eye's pupil (not shown in **FIG. 2**). In bright ambient conditions, the pupil's diameter may be as small as about 2 millimeters (mm). Consequently, when the spacing **S** is less than ~2 mm, the fill factor is high enough to ensure that there are no "holes" in the viewing space **30**.

[41] Still referring to **FIG. 2**, alternate embodiments of the viewing space **30** are contemplated. For example, the viewing space **30** and the beamlets **32** may have apertures other than hexagonal. Furthermore, the aperture of the beamlets **32** need not be a scaled-down version of the aperture of the viewing space **30**. For example, the viewing space **30** may have an elongated hexagonal aperture and the beamlets **32** may have a symmetrical hexagonal aperture as shown in **FIG. 2**. Moreover, the expanded-beam intensity profile within the viewing space **30** may not be substantially uniform, yet may still yield an image of acceptable quality in at least some locations within the viewing space. In addition,

the cross section **34** may be curved instead of planar. For example, the cross section **34** may have a curvature corresponding to the arc swept by the operator's eyes in one or both of the *x* and *y* dimensions. Furthermore, although only one cross section **34** is shown in **FIG. 2**, it is understood that the viewing space **30** includes an infinite number of cross sections that are parallel to the cross section **34**. Moreover, the cross section where the beamlets **32** "pivot" may be located other than in the middle ($d/2$) of the viewing space **30**. In addition, although described as comprising visible light, the beamlets **32** may include electromagnetic energy outside of the visible spectrum. For example, the beamlets **32** may include infrared energy such that the operator (not shown in **FIG. 2**) wears infrared goggles (not shown) to view the virtual image within the viewing space **30**.

Heads-Up Display For Generating The Viewing Space Of FIG. 2

[42] **FIG. 3** is a diagram of a scanned-beam heads-up display **40**, which is operable to generate the viewing space **30** of **FIG. 2** according to an embodiment of the invention. Also shown is a wind screen **42** which the display uses as a reflector to direct the virtual image into the viewing space **30**. By using a scanned beam to generate the virtual image, the display **40** may be smaller, have higher performance (eg, superior contrast, sharpness and brightness), be more energy efficient, and/or be easier to calibrate than conventional heads-up displays. Furthermore, where the display **40** includes substantially no scattering surfaces and the scanned beam comprises coherent electromagnetic energy such as laser light, visible speckle in the virtual image may be reduced or eliminated. Moreover, using the display **40** to generate a virtual image of vehicle information may allow one to simplify the physical vehicle information displays within the vehicle. For example, if the display **40** generates a virtual image of the fuel gauge, then one can omit a physical fuel gauge from the vehicle's dashboard.

[43] Still referring to **FIG. 3**, the heads-up display **40** includes a beam generator **44**, a scanner **46**, a scanned-beam-conditioning assembly **48**, which includes a lens **50**, an exit-pupil expander **52**, and a beam-projection assembly **54**, which includes a lens **56** and a reflector **58** or a combined lens-reflector. Both

the beam-conditioning assembly **48** and the beam-projection assembly **54** may be or include respective optical trains.

[44] The beam generator **44** generates a color output beam **60**, and includes image electronics **62**, red (R), green (G), and blue (B) beam sources **64**, **66**, and **68** for respectively generating R, G, and B beams **70**, **72**, and **74**, and a beam-combiner-and-conditioner assembly **76**. Some heads-up displays may alternatively use a single color or a subset of R, G and B. The beam generator may also include other wavelengths of light, for example to further improve color gamut, brightness, etc.

[45] The electronics **62** modulate the R, G, and B beam sources **64**, **66**, and **68**, and thus the beams **70**, **72**, and **74**, such that the output beam **60** has the desired intensity and color content for a pixel of the image that the electronics is currently generating. The electronics **62** may modulate the beam sources using time modulation, where a beam is full "on" for a predetermined portion of the pixel-generation time and full "off" for another portion of the pixel-generation time, or using intensity modulation, where the intensity of a beam is modulated to a predetermined level for an entire pixel-generation time.

[46] The beam sources **64**, **66**, and **68** may be conventional R, G, and B lasers or light-emitting diodes (LEDs), and the beams **70**, **72**, and **74** may propagate to the beam-combiner-and-conditioner assembly **76** through the air (or other medium) or via an optical fiber (or other optical path). For example, coupling a laser beam from one of the beam sources **64**, **66**, or **68** to the assembly **76** via a single-mode optical fiber may improve the quality of the beam at the assembly as compared to a beam that propagates to the assembly through a medium such as air. Furthermore, coupling a laser beam to the assembly **76** via an optical fiber allows the corresponding beam source to be located remotely from the rest of the display **40**, such as in the trunk of an automobile (not shown in **FIG. 3**). Remotely locating a beam source **64**, **66**, or **68** may be advantageous where the beam source is a gas laser or otherwise is relatively large or dissipates a relatively large amount of heat. Alternatively, if a beam source **64**, **66**, or **68** is a semiconductor laser or LED, then it may be located near the assembly **76**. Moreover, some of the beam sources **64**, **66**, and **68** may be disposed in

locations remote from the assembly **76**, and others of the beam sources may be disposed in locations local to the assembly.

[47] The beam-combiner-and-conditioner assembly **76**, which is further discussed below in conjunction with **FIGS. 4-6**, combines the R, G, and B beams **70, 72, and 74** into the output beam **60**, and imparts to the output beam a top-hat intensity profile and the same hexagonal shape (or scaled version thereof) as the beamlets **32** of **FIG. 2**.

[48] The scanner **46** sweeps the output beam **60** in two dimensions (e.g. vertical and horizontal) to generate the virtual image viewed by the operator (not shown in **FIG. 3**) in the viewing space **30** — two positions of the swept output beam are shown emanating from the scanner in dashed line. The scanner **46** may be a conventional microelectromechanical system (MEMS) scanner, or other type of scanner. A MEMS scanner typically sweeps the output beam **60** sinusoidally, *i.e.*, resonantly, in the horizontal dimension, and linearly in the vertical dimension, although a MEMS scanner may sweep the beam resonantly in the vertical dimension as well. The resonant operation allows the MEMS scanner to consume little power, and the relatively small size of the MEMS scanner may allow the heads-up display **40** to be more compact and lighter than conventional heads-up displays. Examples of a MEMS scanner suitable for use as the scanner **46** is further discussed in U.S. Patent Application Number 10/984,327, entitled MEMS DEVICE HAVING SIMPLIFIED DRIVE, invented by Randall B. Sprague et al., filed November 9, 2004, which is hereby incorporated by reference.

[49] The scanned-beam conditioning assembly **48** conditions the swept output beam **60** for input to the exit-pupil expander **52**. For example, the lens **50** is a conventional telecentric lens that causes the swept output beam **60** to enter the exit-pupil expander **52** normal to the focal plane (not shown) of the expander regardless of the beam's angular position. Furthermore, as discussed in more detail below, the assembly **48** may include other conventional components such that at the input plane of the expander **52**, the intensity profile of the beam **60** is the spatial Fourier Transform in both phase and amplitude of the beam's intensity profile at the output of the beam generator **44**.

[50] The exit-pupil expander **52**, which is discussed further below in conjunction with **FIGS. 7-18**, converts the swept beam **60** at the expander's input plane into an expanded beam **78**, which includes the beamlets **32** (**FIG. 2**) within a beam envelope **79** — two positions of the beam envelope are shown in dashed line. The expanded beam **78** is a larger, *i.e.*, expanded, version of the beam **60**, and eventually forms the viewing space **30**. That is, the expanded beam **78** effectively “sweeps out” the viewing space **30**. More specifically, as the scanner **46** sweeps the beam **60**, the beamlets **32** within the beam envelope **79** generate the image in the viewing space **30** by sweeping across the retinas of the operator's eyes (not shown in **FIG. 3**). As further discussed below, the expander **52** may be a diffractive, refractive, reflective, or combination optical element.

[51] The beam-projection assembly **54** conditions the expanded beam **78** from the exit-pupil expander **52** for direction into the viewing space **30** by the wind screen **42**. For example, the lens **56** is a conventional focusing lens, and the reflector **58**, which is discussed further below in conjunction with **FIG. 20**, is an aspheric mirror having a curvature designed to optically “match” the curvature of the wind screen **42**. The assembly **54** may also include a negative-power lens (not shown in **FIG. 3**) at the output of the exit-pupil expander **52** to further expand the beam **78** before it propagates to the lens **56**. Furthermore, as discussed in more detail below, the assembly **54** may include other conventional components such that at the cross section **34** (**FIG. 2**) of the viewing space **30**, the intensity profile of the beam envelope **79** is the spatial Fourier Transform in both phase and amplitude of the intensity profile of the beam envelope at the output plane (not shown in **FIG. 3**) of the exit-pupil expander **52**, and the intensity profile of the beamlets **32** is the spatial Fourier Transform in both phase and amplitude of the intensity profile of the scanned output beam **60** at the input plane (not shown in **FIG. 3**) of the exit-pupil expander.

[52] Although the wind screen **42** need not be part of the heads-up display **40**, it is typically the final optical component that directs the expanded beam **78** from the reflector **58** to the viewing space **30**. For example, a region **80** of the wind screen **42** that directs the expanded beam **78** is usually located in the lower third of the wind screen, although other parts of the wind screen may be

used. This region may optionally be treated with one or more optical coatings to enhance the wind screen's reflection of the expanded beam. For example, the region **80** may be treated with narrow-band optical coatings that reflect the R, G, and B wavelengths that compose the expanded beam **78** but that pass other wavelengths. It has been found that such coatings have a negligible affect on the level of the wind screen's transparency, and, therefore, have little or no adverse affect on the operator's ability to see through the region **80** of the wind screen **42**.

[53] Still referring to **FIG. 3**, the operation of the heads-up display **40** is discussed according to an embodiment of the invention.

[54] The image electronics **62** modulates the beams **70**, **72**, and **74** to generate the pixels of the image to be scanned. A range of image aspect ratios may be used. In some examples, the image has an aspect ratio between approximately 2:1 and 3:1, for example, 600 pixels wide (horizontal (**x**) dimension) by 200 pixels high (vertical (**y**) dimension). In a typical automotive application where the heads-up display angular field of vehicle is 6 x 2 degrees, this translates into a resolution in the viewing space **30** of approximately 100 pixels per degree, which is greater than the approximately 60 pixels-per-degree resolution of the human eye. Such a high number of pixels-per-degree may be used to make text and graphics appear to the operator to have high definition and sharpness, compared to lower resolution displays. In some applications, a relatively high number of nominal pixels-per-degree can be used to adjust or compensate the shape of the image (for example, to compensate for wind screen curvature tolerances) without substantial loss of effective resolution visible to the eye.

[55] The beam generator **44** generates from the modulated beams **70**, **72**, and **74** the output beam **60** having a substantially top-hat (*i.e.*, substantially uniform) intensity profile and a hexagonal aperture that is substantially the same shape as the hexagonal aperture of the beamlets **32** (**FIG. 2**).

[56] The scanner **46** vertically and horizontally sweeps the beam **60**, which propagates to the exit-pupil expander **52** via the scanned-beam conditioning assembly **48**.

[57] The optical components of the beam-combining-and-conditioning assembly **76** and the scanned-beam conditioning assembly **48** together transform the top-hat intensity profile and hexagonal aperture of the beam **60** at the input plane of the exit-pupil expander **52** into the spatial Fourier Transform, in both
5 phase and amplitude of the top-hat profile and hexagonal aperture at the input of the exit-pupil expander **52**. Because the spatial Fourier Transform of a top-hat profile is a spatial sinc ($\sin(x)/x$) function, the beam **60** has a two-dimensional sinc-like intensity profile at the input plane of the exit-pupil expander **52**.

[58] The exit-pupil expander **52** effectively converts the sinc-like intensity
10 profile of the beam **60** at its input plane into the beam envelope **79**, which also has a sinc-like intensity profile at the output plane of the expander. Furthermore, as discussed below in conjunction with **FIG. 7**, overlap of neighboring sinc-like outputs in the near-field of the expander **52** form beamlets **32** in the substantially uniform far field of the expander, each of which also has an intensity profile
15 similar to the profile out of the aperture. Because the expanded beam profile is a result of diffraction, the beam envelope **79** is sometimes called a diffraction envelope. The beamlets **32** are introduced within this diffraction envelope from the interference of diffraction envelopes from neighboring pixels.

[59] The expanded-beam projection assembly **54** projects the expanded
20 beam **78** onto the wind screen **42**, which directs the expanded beam into the viewing space **30**.

[60] The wind screen **42** and the optical components of the beam-
projection assembly **54** together transform the sinc-like intensity profiles of the
beam **60** and the beam envelope **78** into the respective spatial Fourier
25 Transforms, in both phase and amplitude, of these sinc-like intensity profiles in the viewing space **30**. Because the spatial Fourier Transform of a sinc function is a top-hat profile, the beam envelope **79** has, in the viewing space **30**, a substantially uniform intensity profile and the hexagonal aperture shown in **FIG. 2**. As discussed above in conjunction with **FIG. 2**, the beam envelope **79** defines the
30 **x-y** dimensions of the viewing space **30**, and thus has the same aperture as the cross section **34** of the viewing space. Moreover, as discussed further below in conjunction with **FIG. 8**, the hexagonal aperture of the beam envelope **79**

depends only on the structure of the exit-pupil expander **52**, and is, therefore, independent of the aperture of the beam **60**. In addition, because the spatial Fourier Transform of the beamlet sinc functions is a top-hat profile with a hexagonal aperture, each beamlet **32** (**FIG. 2**) has a substantially uniform intensity profile and an aperture having substantially the same hexagonal shape as the aperture of the beam **60** does.

[61] Furthermore, an operator (not shown in **FIG. 3**) may rotate the reflector **58** about an axis **82**, which is normal to the page of **FIG. 3**, to adjust the position of the viewing space **30** in the vertical (y) dimension.

10 [62] Still referring to **FIG. 3**, alternate embodiments of the heads-up display **40** are contemplated. For example, the display **40** may generate a monochrome image instead of a color image, and thus two of the three beam sources **64**, **66**, and **68** may be omitted from the beam generator **44**, and the beam-combining function may be omitted from the assembly **76**. Furthermore, 15 the telecentric lens **50** may be omitted from the scanned-beam conditioning assembly **48** as discussed further below in conjunction with **FIGS. 13** and **17**. Moreover, although described as generating a virtual image for viewing by an operator of a vehicle, the display **40** may be constructed and disposed for generating an image for viewing by another occupant of the vehicle. For 20 example, the display **40** may play a movie for one or more passengers. The display **40** may reflect the movie off of a portion of the wind screen **42** remote from the operator, or from a surface within the vehicle other than the wind screen, and this surface may be transparent, opaque, or partially transparent. Because such a movie comprises a stream of virtual images, a passenger watching the 25 movie is less likely to experience motion sickness than if he were watching the movie on a conventional movie player. In addition, the display **40** may be used in systems other than a vehicle. Furthermore, the telecentric lens **50**, the exit-pupil expander **52**, and a negative power lens (not shown) at the output of the expander for further expanding the beam **78** may be integrated into a single unit. 30 Moreover, one may replace the telecentric lens **50** with a graded-index-of-refraction (GRIN) lens, which can be integrated with the exit-pupil expander **52** into a single unit. In addition, the aperture of the beam envelope **79** may be

annular such that the beam envelope has a "hole" in it. Furthermore, the display **40** may generate other types of images, such as a map or a telephone directory.

[63] **FIG. 4** is a diagram of the beam-combining-and-conditioning assembly **76** of **FIG. 3** according to an embodiment of the invention.

5 **[64]** The assembly **76** includes three optical trains **90**, **92**, and **94**, each for conditioning a respective one of the R beam **70**, the G beam **72**, and the B beam **74**, and also includes a conventional beam-combining X cube **96**, which combines the conditioned beams from the three optical trains into the output beam **60**.

10 **[65]** The optical train **90** includes a collimating lens **98**, a top-hat converter **100**, a hexagonal clipping aperture **102**, and an optional focusing lens **104**, which are all designed for the wavelength of the R beam **70**. In one example, the wavelength of the R beam **70** is between 635 and 660 nanometers (nm).

15 **[66]** Similarly, the optical train **92** includes a collimating lens **106**, a top-hat converter **108**, a hexagonal clipping aperture **110**, and an optional focusing lens **112**, which are all designed for the wavelength of the G beam **72**, and the optical train **94** includes a collimating lens **114**, a top-hat converter **116**, a hexagonal clipping aperture **118**, and an optional focusing lens **120**, which are all
20 designed for the wavelength of the B beam **74**. In one example, the wavelengths of the G beam **72** and the B beam **74** are between 440 and 490 nm and between 500 and 550 nm, respectively.

[67] The X-cube **96** includes a first inner surface **122**, which is treated with an optical coating that passes the conditioned G and B beams but that
25 reflects the conditioned R beam, and includes a second inner surface **124**, which is treated with an optical coating that passes the conditioned R and G beams but that reflects the conditioned B beam.

[68] The operation of the beam-combining-and-conditioning assembly **76** according to an embodiment of the invention is discussed below in conjunction
30 with **FIGS. 4** and **5**. But first, **FIG. 5** is discussed.

[69] FIG. 5 is a plot of a Gaussian intensity profile **126** of an input beam, such as one of the beams **70**, **72**, and **74** of FIG. 4, laid over a plot of a top-hat intensity profile **128** of an output beam, which is generated by passing the input beam through a top-hat converter, such as one of the converters **100**, **108**, and
5 **116** of FIG. 4, according to an embodiment of the invention. Although this plot is two dimensional, because the input and output beams are symmetrical, the plot represents any "slice" of these beams that is coplanar with the beams' center axis **130**. That is, one can form a three-dimensional plot of the input and output
10 beams' intensity profiles by spinning this two-dimensional plot about the beams' center axis **130**.

[70] The input beam (the beam having the intensity profile **126**) has a maximum relative intensity of approximately 1 at its center axis **130**, and the intensity tails off symmetrically according to a Gaussian function as one moves
15 away from the center axis. Theoretically, a Gaussian function approaches, but never equals, zero; consequently, the input beam theoretically has an infinite aperture. Therefore, to aid discussion, one defines the full-width at half maximum (FWHM) of the beam as the width of the beam at the point where it has $\frac{1}{2}$ of its maximum intensity. In this example, at the point where the input beam has an
20 intensity = $\frac{1}{2} \times 1 = 50\%$, it has a relative width of 1; therefore, the input beam has a relative FWHM of 1.

[71] In contrast, the output beam (the beam having the intensity profile **128**) has a uniform (flat) intensity of approximately 35% across virtually its entire width of approximately 2 times the FWHM width of the input Gaussian. Consequently, the top-hat converter through which the input beam having the
25 Gaussian intensity profile **126** propagates redistributes the intensity of the input beam to form an output beam having the top-hat intensity profile **128**. Of course, one can adjust the dimensions and other properties of the top-hat converter to vary the width and intensity of the output beam. Thus, in general, for an input beam having a Gaussian intensity profile, the smaller the width of the top-hat
30 output beam, the higher the intensity of the output beam, and vice versa.

[72] Referring again to FIG. 4, the operation of the beam-combining-and-conditioning assembly **76** is discussed where each of the beams **70**, **72**, and **74**

has a Gaussian intensity profile such as the Gaussian intensity profile **126** of **FIG. 5**. Furthermore, for clarity, only the operation of the optical train **90** is discussed in detail, it being understood that the optical trains **92** and **94** operate in a similar manner.

5 **[73]** First, the collimating lens **98** collimates the aperture of the R beam **70**.

[74] Next, the top-hat converter **100** converts the collimated R beam **70** having a Gaussian intensity profile (**FIG. 5**) into an R beam having a top-hat intensity profile (**FIG. 5**) in a conventional manner.

10 **[75]** Then, the aperture **102** clips the beam output from the top-hat converter **100** to impart a hexagonal aperture to the beam, the hexagonal aperture being approximately the same shape as the aperture of the beamlets **32** of **FIG. 2**.

[76] Next, the focusing lens **104** passes the R beam **70** from the
15 aperture **102** to the X-cube surface **122**, which reflects the beam to form the R component of the output beam **60**. One function of the focusing lens **104** is to condition the R component of the output beam **60** such that at the input plane (not shown in **FIG. 4**) of the exit-pupil expander **52** (**FIG. 3**), the intensity profile of the output beam is the spatial Fourier Transform, in both phase and amplitude, of the
20 intensity profile of the output beam as it exits the X cube **96**. Consequently, the focusing lens **104** (and the focusing lens **112** and **120**) may be omitted where other techniques are used to obtain this Fourier Transform relationship. For example, the focusing lens **104** (and the focusing lens **112** and **120**) may be omitted when the telecentric lens **50** is omitted from the scanned-beam
25 conditioning assembly **48** (**FIG. 3**).

[77] The optical trains **92** and **94** each operate in a similar manner on the G and B beams, respectively, and the X-cube **96** passes the G beam and the surface **124** reflects the B beam to form the color output beam **60** by
 "overlapping" the reflected R and B beams and the passed G beam. The output
30 beam **60** has a top-hat intensity profile with an intensity level substantially equal to

the sum of the intensities of the R, G, and B beams, and has substantially the same hexagonal aperture as each of the R, G, and B beams.

[78] FIG. 6 is a diagram of the beam-combining-and-conditioning assembly 76 according to another embodiment of the invention. One difference
5 between the assemblies 76 of FIGS. 4 and 6 is that the assembly of FIG. 6 includes a reduced number of components, and thus may be smaller, easier to manufacture, and less expensive than the assembly of FIG. 4.

[79] The assembly 76 includes three collimating lens 140, 142, and 144, each for collimating a respective one of the R beam 70, the G beam 72, and the B
10 beam 74, the beam-combining X cube 96, which combines the collimated beams from the three optical trains into an intermediate beam 146, and an optical train 148, which converts the intermediate beam into the output beam 60.

[80] The optical train 148 includes an achromatic (*i.e.*, multi-wavelength) top-hat converter 150, an achromatic hexagonal aperture 152, and an optional
15 achromatic focusing lens 154, which are designed for the wavelengths of the R, G, and B beams 70, 72, and 74 in a conventional manner. In one example, the R, G, and B beams have the same respective wavelengths as discussed above in conjunction with FIG. 4.

[81] Still referring to FIG. 6, the operation of the beam-combining-and-conditioning assembly 76 is discussed according to an embodiment of the
20 invention where each of the input R, G, and B beams 70, 72, and 74 has substantially the same Gaussian intensity profile such as the profile 126 of FIG. 5.

[82] First, the collimating lenses 140, 142, and 144 respectively collimate the R, G, and B beams 70, 72, and 74.

25 [83] Next, the X-cube 96 passes the G beam, and the surfaces 122 and 124 respectively reflect the R and B beams such that the reflected R and B beams "overlap" the G beam to form the color intermediate beam 146 having substantially the same Gaussian intensity profile as the input R, G, and B beams 70, 72, and 74.

[84] Then, the top-hat converter **150** conventionally converts the intermediate beam **146** into a beam having a top-hat intensity profile such as the profile **128** of **FIG. 5**.

[85] Next, the aperture **152** clips the beam from the top-hat converter **150** to impart a hexagonal aperture to the beam, the hexagonal aperture being approximately the same shape as the apertures of the beamlets **32** (**FIG. 2**).

[86] Then, the focusing lens **154** receives the beam from the aperture **152** and generates the output beam **60**, which has the top-hat intensity profile and the hexagonal aperture. For reasons similar to those discussed above in conjunction with **FIGS. 4** and **5**, the focusing lens **154** may be omitted.

[87] Referring again to **FIGS. 4 – 6**, alternate embodiments of the beam-combining-and-conditioning assembly **76** are contemplated. For example, although shown as respective single optical components, one or more of the top-hat converters **100**, **108**, **116**, and **150** may each include multiple optical components. Furthermore, one can replace the X-cube **96** with a slab beam combiner such as the one disclosed in U.S. Patent Application Ser. No. 10/828,876, filed April 23, 2004, and which is incorporated by reference. In addition, one can omit one or more of the top-hat converters and design the one or more of the corresponding clipping apertures **102**, **110**, **118**, and **152** to have a clipping width equal or approximately equal to the FWHM width of the corresponding R, G, or B beams and the intermediate beam **146**. For example, where a beam has the Gaussian intensity profile **126** (**FIG. 5**) this clipping technique will impart to the beam **60** the top portion of the profile **126**, *i.e.*, the profile **126** with the all portions of the beam blocked beyond a relative width of +/- 0.5 from the center axis **130**. This to portion of the Gaussian profile **126** roughly approximates a top-hat profile. But although such an embodiment reduces the number of optical components in the assembly **76**, it is less efficient because it discards more beam energy than embodiments, such as the embodiments of **FIGS. 4** and **6**, which use a top-hat converter. Furthermore, because this embodiment does not impart a true top-hat intensity profile to the output beam **60**, the beamlets **32** (**FIG. 2**), and thus the expanded beam **78**, may have a non-uniform intensity profile within the viewing space **30**.

[88] **FIG. 7** is a side view of the exit-pupil expander **52** of **FIG. 3** according to an embodiment of the invention. In this embodiment, the expander **52** is a dual-microlens array (DMLA), the structure and operation of which are thoroughly discussed in "A Novel Approach for Exit Pupil Expansion in Wearable Displays", Karlton Powell, et al., "Exit Pupil Expander: Image Quality Performance Enhancements and Environmental Testing Results", Karlton Powell, et al., U.S. provisional application Serial No. 60/541,619 filed on February 4, 2004, which are incorporated by reference. Therefore, for brevity, only an overview of the DMLA is presented below.

10 [89] The DMLA exit-pupil expander **52** includes first and second microlens arrays (MLAs) **160** and **162**, which are made from a transparent optical material such as plastic or glass and which include a number of lenslets **164** and **166**, respectively. The MLA **160** has focal plane **168** and a focal length f from the focal plane; likewise, the MLA **162** has a focal plane **170**, and the same focal
15 length f from the focal plane **170**. The MLAs **160** and **162** are positioned such that their focal planes **168** and **170** are separated by the focal length f , and the gap between the MLAs is filled with air. Each lenslet **164** and **166** has a width D , which is the pitch of the MLAs **160** and **162**, and each lenslet **164** is aligned with a corresponding lenslet **166**.

20 [90] **FIG. 8** is a plan view of the MLA **160** of **FIG. 7** according to an embodiment of the invention, it being understood that the MLA **162** is similar. The lenslets **164** have a hexagonal footprint, are arranged in a "honeycomb" pattern, and are contiguous such that there are no spaces between adjacent lenslets where the lenslets join the backplane of the MLA **160**.

25 [91] The operation of the DMLA exit-pupil expander **52** is discussed in conjunction with **FIGS. 7 – 8** according to an embodiment of the invention where the width of the scanned beam **60** as it exits the beam generator **44** (**FIG. 3**) is approximately D , the footprint of each of the lenslets **164** and **166** has the same hexagonal shape as the output beam's aperture, and the output beam's aperture
30 has the same orientation as the footprints of the lenslets.

[92] As discussed above in conjunction with FIG. 3, the scanned-beam conditioning assembly 48 causes the intensity profile of the scanned beam 60 to be sinc-like at the input of the DMLA exit-pupil expander 52.

[93] When the beam 60 is centered on a lenslet 164a, the corresponding lenslet 166a outputs an expanded center beam 172 also having a sinc-like intensity profile.

[94] As discussed above in conjunction with FIG. 3, the expanded-beam projection assembly 54 performs a spatial Fourier Transform in phase and amplitude on the expanded center beam 172 within the viewing space 30.

[95] Consequently, ignoring side beams (discussed below) for the moment, in the viewing space 30 the center beam 172 is bounded by the hexagonal beam envelope 79 and has a uniform intensity profile and no beamlets 32. That is, the envelope 79 effectively bounds a single beamlet, the center beam 172, which has a top-hat intensity profile within the viewing space 30 (FIG. 2). Furthermore, the hexagonal aperture of the beam envelope 79 and the center beam 172 is due to the honeycomb layout of the MLAs 160 (FIG. 8) and 162 and the hexagonal aperture of the lenslets 164 and 166, but is independent from the aperture of the beam 60. That is, the beam envelope 79 and the center beam 172 would still have a hexagonal aperture even if the aperture of the beam 60 was other than hexagonal. Moreover, because the center beam 172 is generated by refraction, the beam envelope 79 is independent of wavelength. That is, the beam envelope 79 has the same aperture regardless of the wavelength or wavelengths of light that compose the scanned beam 60.

[96] But because the intensity profile of the beam 60 is sinc-like at the input of the DMLA exit-pupil expander 52 (also the case for Gaussian or truncated Gaussian beams), some of the beam energy is incident on the adjacent lenslets 164b and 164c, thus causing the corresponding lenslets 166b and 166c to output side beams 174 and 176 — because FIG. 7 is a two-dimensional side view, other side beams outside of the plane of FIG. 7 may exist. Furthermore, even if none of the beam energy is incident on the adjacent lenslets 164b and 164c when the beam 60 is centered on the lenslet 164a, the beam 60 still overlaps multiple

lenslets as the scanner **46** (**FIG. 3**) sweeps the beam from one lenslet to another, and this overlapping gives rise to output side beams **174** and **176**.

[97] Still referring to **FIGS. 7-8**, the side beams **174** and **176** interfere with the expanded center beam **172** in the far field, and this diffraction phenomenon yields the expanded beam **78** having the beamlets **32**, which are sometimes called diffraction orders. As discussed above in conjunction with **FIG. 3**, the hexagonal aperture and top-hat intensity profile of the beamlets **32** within the viewing space **30** are the same as the aperture and the intensity profile of the output beam **60** as it exits the beam generator **44**; but the aperture and intensity profile of the beamlets are independent of the layout pattern and aperture of the lenslets **164** and **166**. Furthermore, because the beamlets **32** are generated by interference of overlapping diffraction envelopes, the size of the beamlet aperture is dependent on wavelength. Consequently, one may design the DMLA exit-pupil expander **52** for the center wavelength, for example the wavelength of the G component, of the scanned beam **60**.

[98] In summary, the intensity profile of the beam envelope **79** depends only on the optical properties of the DMLA exit-pupil expander **52**, the aperture of the beam envelope **79** depends only on the layout pattern and aperture of the lenslets **164** and **166**, the intensity profile of the beamlets **32** depends only on the intensity profile of the scanned beam **60**, and the aperture of the beamlets depends only on the aperture of the scanned beam.

[99] Still referring to **FIGS. 7** and **8**, alternate embodiments of the exit-pupil expander **52** are contemplated. For example, the gap between the MLAs **160** and **162** may be filled with a transmission medium other than air. For example, the fill medium may be a solid to resist gap compression or expansion that may alter the optical properties of the DMLA expander **52**, and one can alter the properties (e.g., pitch, lenslet curvature, index of refraction) of the MLAs **160** and **162** in a conventional manner to compensate for the different index of refraction (relative to the index of refraction of air) of the filler medium. Additional embodiments are discussed below in conjunction with **FIGS. 13-18**.

[100] **FIGS. 9A – 11B** illustrate the dependence of the intensity profile of the expanded beam **78** (**FIGS. 3** and **7**) within the viewing space **30** on the

intensity profiles of the beam envelope **79** (**FIGS. 2** and **7**) and the beamlets **32** (**FIG. 2**), and artifacts caused by the expanded beam having a non-uniform intensity profile. As discussed below, artifacts such as "banding" may be more severe when an operator's eye is outside of the cross section **34** of the viewing space **30**.

[101] **FIG. 9A** shows the beam envelope **79** having a uniform (flat) intensity profile, and **FIG. 9B** shows that the beamlets **32**, which each have a non-uniform, Gaussian-like intensity profile, combine to yield a non-uniform beamlet intensity profile within the beam envelope **79**.

[102] **FIG. 9C** shows the non-uniform intensity profile of the expanded beam **78** within the viewing space **30** resulting from the beam-envelope and combined-beamlet intensity profiles of **FIGS. 9A** and **9B**. Each sinc-like beam output **172**, **174**, and **176** at the exit-pupil expander **52** transforms into a top-hat intensity profile in the far field. Interference due to overlap of these beam outputs **172**, **174**, and **176** forms beamlets **32** at a spacing defined by the lenslet array pitch and layout. The envelope of the input beam **60** in phase and amplitude transforms to form the intensity profile of each beamlet **32** in the far-field within the expanded beam **78**. Thus it can be considered that the resulting intensity profile of the expanded beam **78** is a convolution, in phase and amplitude of the expanded beam-envelope of **FIG. 9A**, the beamlet envelope, and the beamlet spacing and layout of **FIG. 9B**. Consequently, even though the beam-envelope intensity profile (**FIG. 9A**) is uniform, the non-uniformity of the combined-beamlet intensity profile (**FIG. 9B**) causes the intensity profile of the expanded beam **78** to be non-uniform. And although not shown, a uniform combined-beamlet intensity profile combined with a non-uniform beam-envelope intensity profile also yields a non-uniform resulting intensity profile.

[103] **FIGS. 10A** and **10B** illustrate intensity patterns perceived by an operator (not shown in **FIGS. 10A** and **10B**) for different eye positions within the viewing space **30** for a non-uniform expanded-beam intensity profile similar to that of **FIG. 9C**. And discussed below are artifacts that can arise when the expanded-beam intensity profile is not uniform throughout the viewing space.

[104] FIG. 10A illustrates a first expanded beam **78a** that generates a first pixel at the top of a virtual image, and a second expanded beam **78b** that generates a second pixel at the bottom of the image, each expanded beam having the same non-uniform intensity profile. Although the first and second
5 pixels, and thus the first and second expanded beams **78a** and **78b**, are generated at different times, both are shown in FIG. 10A for purposes of illustration. Furthermore, other expanded beams are generated between the expanded beams **78a** and **78b** to generate corresponding pixels between the first and second pixels, but these other expanded beams are omitted for clarity.

10 [105] For a single expanded beam **78**, any cross section within the viewing space **30** has the expanded beam's intensity profile. For example, at the cross sections **180** and **182**, the same non-uniform intensity profile exists within each expanded beam **78a** and **78b**.

[106] At the cross section **34** of the viewing space **30**, the expanded
15 beams **78a** and **78b** overlap at all points such that at each point along the cross section **34**, the expanded-beam intensity profile has the same level for each pixel. For example, at a location **184** or **186**, the intensity-profile level is respectively the same for each expanded beam **78**, and is thus the same for each pixel of the image.

20 [107] But at locations outside of the cross section **34**, the expanded beams **78a** and **78b** do not overlap at all points, and thus the intensity-profile level may change from pixel to pixel. For example, at a location **188** (FIG. 10B), the intensity-profile level changes from pixel to pixel as further explained below.

[108] Therefore, if an operator's eye pupil (not shown in FIGS. 10A and
25 **10B**) is aligned with the cross section **34**, then the operator typically perceives a uniform image intensity if he does not move his eye, but may perceive a non-uniform intensity if and while he moves his eye from one location of the cross section **34** to another location of the cross section **34**. For example, assume that the eye pupil is at the location **184**. Because at the location **184** the level of the
30 expanded-beam intensity profile is the same for each pixel, the operator perceives a uniform intensity profile for the image as long as he does not move his eye from the location **184**. That is, although the absolute intensity at different

locations of the image may change with the image content, the operator does not perceive "banding," where one region of the image has a higher average brightness than another region. But if the operator moves his eye from the location **184** to the location **186**, then he may notice that the image brightness
5 changes while his eye effectively traverses the portion of the non-uniform expanded-beam intensity profile between the locations **184** and **186**.

[109] But if the operator's eye (not shown in **FIGS. 10A** and **10B**) is outside of the cross section **34**, then he may perceive the image having a non-uniform intensity profile even if he does not move his eye. For example,
10 assume that the eye pupil is at the location **188**. Because at the location **188** the expanded beams **78a** and **78b** do not overlap at all points, the level of the expanded-beam intensity profile is different for each pixel. For the pixel carried by the expanded beam **78a**, the operator perceives the intensity-profile end at a point **190** on the expanded-beam intensity profile, and for the pixel carried by the
15 beam **78b**, the operator perceives the intensity-profile level at a point **192** on the expanded-beam intensity profile. That is, as the scanner **46** (**FIG. 3**) sweeps the beam **60** (**FIG. 3**), the expanded beam **78** effectively "pivots" from the position of the beam **78a** to the position of the beam **78b**. During this "pivoting," the portion of the expanded-beam intensity profile between the points **190** and **192** effectively
20 moves past the location **188**, and thus past the operator's eye. Therefore, even without moving his eye, the operator perceives the image as having an intensity profile equal to the portion of expanded-beam intensity profile between the points **190** and **192**. Because this portion of the expanded-beam intensity profile is not uniform, the operator may, depending on the magnitude of the non-uniformity,
25 perceive intensity "banding" even when he is not moving his eye, and may perceive shifting of the "banding" pattern as he moves his eye in any direction. Of course, this "banding" pattern may disappear if the operator moves his eye into alignment with a location of the cross section **34** of the viewing space **30**.

[110] **FIGS. 11A – 12B** illustrate how the heads-up display **40** reduces the
30 severity of, or altogether eliminates, the artifacts discussed above in conjunction of **FIGS. 10A** and **10B** according to an embodiment of the invention. Specifically,

the display **40** generates the expanded beam **78** having a uniform intensity profile as discussed above in conjunction with **FIGS. 4-8**.

5 [111] **FIG. 9A** shows expanded-beam envelope **78** having a uniform intensity profile as discussed above, and **FIG. 11A** shows that the beamlets **32** also each having a uniform intensity profile.

[112] **FIG. 11B** shows the uniform intensity profile of the expanded beam **78** resulting from the uniform beam-envelope and combined-beamlet intensity profiles of **FIGS. 9A** and **11B**. Specifically, the expanded-beam intensity profile is the combination of the beam-envelope intensity profile of **FIG. 9A** with the
10 combined-beamlet intensity profile of **FIG. 11B**. That is, the convolution of uniform beam-envelope and combined-beamlet intensity profiles yields a uniform expanded-beam intensity profile.

[113] **FIG. 12** illustrates intensity patterns perceived by an operator (now shown in **FIG. 12**) for different eye positions within the viewing space **30** for the
15 uniform expanded-beam intensity profile of **FIG. 11B** according to an embodiment of the invention.

[114] More specifically, **FIG. 12** illustrates a first expanded beam **78c** that generates a first pixel at the top of the virtual image, and illustrates a second expanded beam **78d** that generates a second pixel at the bottom of the image.

20 [115] For a single expanded beam **78**, any cross section within the viewing space **30** has the expanded-beam intensity profile of **FIG. 11B**. For example, at the cross sections **200** and **202**, the same uniform expanded-beam intensity profile exists within each expanded beam **78c** and **78d**.

[116] At the cross section **34** of the viewing space **30**, the expanded
25 beams **78c** and **78d** overlap at all points such that at any point along the cross section **34**, the expanded-beam intensity profile is the same for each pixel. Therefore, an operator (not shown in **FIG. 12**) will sense little or no change in the image brightness as he moves his eye from one location of the cross section **34** to another location of the cross section **34**.

30 [117] Furthermore, at locations outside of the cross section **34**, even though the expanded beams **78c** and **78d** do not overlap at all points, the

expanded-beam intensity-profile level is the same for each pixel within the image perceived by an operator. For example, at a location **204**, the intensity-profile level does not change from pixel to pixel because the portion of the intensity profile between points **206** and **208** (same point in **FIG. 12**) is flat. That is, as the expanded beam **78** pivots from the position of the beam **78c** to the position of the beam **78d**, the level of the expanded-beam intensity profile does not change at the point **204**. Therefore, the operator does not perceive "banding" in the image when his eye is outside of the cross section **34**.

[118] Consequently, an operator perceives a substantially uniform image intensity regardless of the location of his eye's pupil within the viewing space **30** and regardless of whether he is moving his eye. That is, because the expanded-beam intensity profile (**FIG. 11B**) is substantially flat, the operator perceives the image having substantially the same uniform intensity profile at any location within the viewing space **30**.

[119] Referring to **FIGS. 11A-12**, alternate embodiments of the invention are contemplated. For example, instead of generating the uniform expanded-beam intensity profile (**FIG. 11B**) by generating uniform intensity profiles for both the beam envelope **79** and the beamlets **32**, the heads-up display **40** (**FIG. 3**) may generate the beam envelope **79** and the beamlets **32** having non-uniform intensity profiles such that the convolution of these non-uniform intensity profiles yields a uniform expanded-beam intensity profile such as shown in **FIG. 11B**.

[120] **FIG. 13** is a plan view of an MLA **210** belonging to a DMLA exit-pupil expander **52** (**FIG. 3**) according to another embodiment of the invention, it being understood that the alternative DMLA includes a second MLA that is similar to the MLA **210** but that is omitted from **FIG. 13** for clarity. The MLA **210** differs from the MLA **160** of **FIG. 8** in that lenslets **212** are not fully contiguous with one another at the MLA backplane, and thus the MLA **210** has spaces **214** between adjacent lenslets **212**. The spaces **214** are often the result of a conventional manufacturing process that does not or cannot form fully contiguous lenslets **212**. But by treating the spaces **214** with an opaque coating, the spaces have little or no adverse affect on the operation of the alternative DMLA. Consequently, when including a DMLA having the MLA **210** and a similar second MLA, the heads-up

display **40** (**FIG. 3**) can generate the viewing space **30** (**FIG. 2**) having substantially the same properties (e.g., uniform expanded-beam intensity profile, hexagonal aperture) as discussed above in conjunction with **FIGS. 3-12**. In a related embodiment, the spaces **214** on only one of the MLAs, such as the MLA and the input side of the DMLA expander **52**, are treated with an opaque coating.

[121] **FIG. 14** is a side view of a DMLA exit-pupil expander **52** according to another embodiment of the invention. The DMLA of **FIG. 14** differs from the DMLA of **FIGS. 7 – 8** in that it includes curved MLAs **220** and **222**, which respectively include lenslets **224** and **226**. Corresponding pairs of lenslets **224** and **226** are aligned such that the scanned beam **60** (**FIG. 3**) follows radial paths **228** that are simultaneously coincident with the center axes of both lenslets of these respective lenslet pairs. Consequently, the curved DMLA allows one to omit the telecentric lens **50** from the scanned-beam conditioner assembly **48** (**FIG. 3**). The MLAs **220** and **222** each have the same focal length f in the radial dimension, and have respective focal curves **230** and **232**, which are spaced apart by f in the radial dimension. Furthermore, the lenslets **224** and **226** are arranged in the honeycomb pattern of **FIGS. 8** and **13**, and the MLAs **220** and **222** may include opaquely coated spaces between the lenslets as discussed above in conjunction with **FIG. 13**. Consequently, when including the DMLA of **FIG. 14**, the heads-up display **40** (**FIG. 3**) can generate the viewing space **30** (**FIG. 2**) having substantially the same properties (e.g., uniform expanded-beam intensity profile, hexagonal aperture) as discussed above in conjunction with **FIGS. 3-12**.

[122] **FIG. 15** is an isometric view of a slab DMLA exit-pupil expander **52** according to another embodiment of the invention. This DMLA includes two MLAs **240** and **242**, which are each formed from a respective pair of slabs **244** and **246**, and **248** and **250**, of semi-cylindrical lenses each having the same pitch. The slab **244** is orthogonal to the slab **246**, and the slab **248** is orthogonal to the slab **250**. The MLAs **240** and **242** each have the same focal length f , and have respective focal planes **252** and **254**, which are spaced apart by f . The resulting lenslets of each MLA **240** and **242** are effectively arranged in a square pattern, not a hexagonal pattern; consequently, the resulting lenslets cause the beam

envelope **79** (**FIG. 3**) to have a square shape. Therefore, to improve the fill factor, one can modify the beam generator **44** (**FIG. 3**) to impart a square aperture to the output beam **60**, and thus to the beamlets **32** (**FIG. 2**).

[123] Still referring to **FIG. 15**, alternative embodiments of the slab DMLA exit-pupil expander **52** are contemplated. For example, one slab of each MLA **240** and **242** can have a different pitch than the other slab so that the resulting lenslets have a rectangular shape. To improve the fill factor for such an embodiment, one can modify the beam generator **44** (**FIG. 3**) to impart a rectangular aperture to the output beam **60**, and thus to the beamlets **32** (**FIG. 2**).
Furthermore, although shown with the horizontally aligned slabs **246** and **248** facing one another, one can contract the slab DMLA expander **52** with the two vertically aligned slabs **244** and **250** facing one and other, or one vertically aligned slab facing a horizontally aligned slab. Moreover, if there are any spaces between the lenses at the slab backplane, one can treat them with an opaque coating as discussed above in conjunction with **FIG. 13**.

[124] **FIG. 16** is an isometric view of a DMLA exit-pupil expander **52** according to another embodiment of the invention. This DMLA expander **52** includes two lenslet arrays **256** and **258**. The array **256** includes cylindrical lenses **260** having the same pitch and mounted between two slabs **262** and **264** of optical material such as glass or plastic. For example, the cylindrical lenses **260** may be optical fibers. The array **258** is similar to the array **256**, and includes cylindrical lenses **265** having the same pitch and mounted between two slabs **266** and **267** of optical material such as glass or plastic such that the lenses **265** are orthogonal to the lenses **260**. The resulting lenslets are arranged in a square pattern and cause the expanded-beam envelope **79** (**FIG. 3**) to have a square shape. Therefore, one can modify the beam generator **44** (**FIG. 3**) to impart a square aperture to the output beam **60**, and thus to the beamlets **32** (**FIG. 2**). Moreover, to mask spaces between the lenses **260** and **265**, one can treat corresponding regions of the slabs **262**, **264**, **266**, and **267** with an opaque coating as discussed above in conjunction with **FIG. 13**.

[125] **FIG. 17** is a side view of a reflective DMLA exit-pupil expander **52** according to another embodiment of the invention. Like the DMLA expander **52**

of **FIGS. 7-8**, the reflective DMLA expander includes the MLA **160**. But the reflective DMLA expander **52** differs from the DMLA expander of **FIGS. 7 – 8** in that it includes a reflector **270** instead of the MLA **162**. The reflector **270** includes a planar reflecting surface **272** that is located $f/2$ from the focal plane **168** of the MLA **160**. Consequently, the expanded beam **78** propagates to the viewing space **30** (**FIG. 2**.) from a front side **274** (*i.e.*, the same side into which the scanned beam **60** propagates) of the MLA **160**. Therefore, when incorporating the reflective DMLA expander **52** of **FIG. 17**, the heads-up display **40** (**FIG. 3**) can generate the viewing space **30** (**FIG. 2**) having substantially the same properties (e.g., uniform expanded-beam intensity profile, hexagonal aperture) as discussed above in conjunction with **FIGS. 3-12**. Furthermore, the reflective DMLA expander **52** may be easier to manufacture than the DMLA expander **52** of **FIGS. 7 – 8** because it does not require alignment of two MLAs.

[126] **FIG. 18** is a side view of a multi-pitch DMLA exit-pupil expander **52** according to another embodiment of the invention. Like the DMLA expander **52** of **FIGS. 7 – 8**, the multi-pitch DMLA expander includes the MLA **160** having the lenslet pitch D . But the multi-pitch DMLA expander **52** differs from the DMLA expander of **FIGS. 7 – 8** in that it includes a second MLA **280** having a different lenslet pitch $D' > D$, which allows one to omit the telecentric lens **50** from the scanned-beam conditioning assembly **48** (**FIG. 3**). The MLA **280** has a focal length f , a focal plane **282** that is located a distance f from the focal plane **168** of the MLA **160**, and lenslets **284** that are arranged in a honeycomb pattern similar to the pattern of the MLA **160** as shown in **FIG. 8**. Consequently, when incorporating the multi-pitch DMLA expander **52**, the heads-up display **40** (**FIG. 3**) can generate the viewing space **30** (**FIG. 2**) having substantially the same properties (e.g., uniform expanded-beam intensity profile, hexagonal aperture) as discussed above in conjunction with **FIGS. 3-12**. In an alternative embodiment of the multi-pitch DMLA expander **52**, D' is less than D .

[127] **FIG. 19** is an isometric view of a single-microlens-array (SMLA) exit-pupil expander **52** according to another embodiment of the invention. As its name implies, the SMLA expander **52** includes a single MLA **290**. Like the lenslets **164** of the MLA **160** (**FIGS. 7 and 8**), lenslets **292** of the MLA **290** are

arranged in a honeycomb pattern per **FIG. 8**. But unlike the MLA **160** of **FIGS. 7 – 8**, the MLA **290** includes lenslets **292** having different properties, e.g., height, radius of curvature, pitch, and index of refraction. Furthermore, the arrangement of the different lenslets **290** may be pseudo-random or ordered such that a group of lenslets may share the same properties. Although the SMLA expander **52** may be easier and less expensive to manufacture than the DMLA expander **52** of **FIGS. 7 - 8**, the SMLA may be unable to generate the parameters (e.g., expanded-beam intensity profile,) of the viewing space **30** as close to the desired levels as the DMLA expander **52** of **FIGS. 7 – 8** can generate these parameters.

10 **[128]** Referring again to **FIGS. 7-8** and **13 -19**, additional embodiments of the exit-pupil expander **52** (**FIG. 3**) are contemplated. For example, one may design an exit-pupil expander **52** by combining selected features shown in any of the **FIGS. 7-8** and **13-19**. In one such example, one can modify the curved DMLA expander **52** of **FIG. 14** by replacing the curved MLA **222** with a curved reflector in a manner similar to that shown in **FIG. 17**. Furthermore, one can use an ordered or random-ordered diffuser, such as a diffraction grating, for the exit-pupil expander **52**. An example of a suitable diffraction grating is discussed in U.S. patent application Serial No. 10/205,858 filed July 26, 2002, U.S. patent application Serial No. 10/889,963 filed July 12, 2004, U.S. patent application Serial No. 10/890,501, filed July 12, 2004, and U.S. Patent No. 6,768,588, issued on July 27, 2004, which are incorporated by reference.

[129] **FIG. 20** is an isometric view of a portion of the expanded-beam projection assembly **54** (**FIG. 3**) and a dashboard shield **300** according to an embodiment of the invention. In addition to the aspheric mirror **58**, the assembly **54** includes a mirror **302**, mirror **304**, and a cylindrical mirror **306**.

[130] The operation of the illustrated portion of the expanded-beam projection assembly **54** is discussed according to an embodiment of the invention. The mirror **302** directs the expanded beam **78** (which includes the beamlets **32** (**FIG. 2**) within the beam envelope **79** (**FIG. 3**)) onto the mirror **302**, which directs the expanded beam **78** onto the mirror **306**. The mirror **306**, which is curved away from the mirror **58**, further expands the expanded beam **78**, and directs the

expanded beam onto the aspheric mirror **58**, which directs the expanded beam through the shield **300** and onto the wind screen **42** (**FIG. 3**).

[131] As discussed above in conjunction with **FIG. 3**, an operator (not shown in **FIG. 20**) may adjust the position of the viewing space **30** (**FIG. 2**) for his particular height by rotating the mirror **58** or the entire heads-up display assembly about an axis **308** to move the viewing space **30** in the vertical (y) dimension. Alternatively, an automatic system (not shown in **FIG. 20**) can adjust the vertical position of the viewing space **30** by so rotating the mirror **58** or the entire heads-up display assembly. Also, as discussed above in conjunction with **FIG. 3**, the curvature of the mirror **58** is designed to optically compensate the curvature of the wind screen **42** so that the expanded beam **78** and displayed image does not stretch, distort or change position significantly as the operator moves their eyes inside the viewing space..

[132] Still referring to **FIG. 20**, the shield **300**, which may optionally be formed to reduce glare, is mounted within an opening formed in the vehicle dashboard (not shown in **FIG. 20**) or on top of the head-up display package to protect the mirror **58** and the other components of the heads-up display **40** (**FIG. 3**) and yet allow the expanded beam **78** (**FIG. 3**) to propagate from the mirror **58** to the wind screen **42** (**FIG. 3**). The shield may also be used to minimize glare from the sun or other external illumination sources that might otherwise be reflected off the heads-up display and into the operators eyes. Both the exposed (top) and unexposed (bottom) surfaces **310** and **312** of the shield **300** are treated with an antireflective coating, and the exposed surface is also treated with an anti-fingerprint coating such as Teflon[®]. Furthermore, the shield **300** may be made from any transparent material such as glass or plastic.

[133] Alternative embodiments of the expanded-beam projection assembly **54** are contemplated. For example, the assembly **54** may include more or fewer mirrors than shown in **FIG. 20**, and may also include refractive, catadioptric and/or diffractive optical elements in addition to or in place of the lens **56** (**FIG. 3**).

[134] **FIGS. 21** and **22** illustrate how one can electronically calibrate the heads-up display **40** (**FIG. 3**) to compensate for image distortion caused by the

wind screen **42** or other factors according to an embodiment of the invention. Because the calibration is done electronically, it is often less complex and less expensive than a calibration technique that requires a modification to or a replacement of a component of the heads-up display **40** such as the aspheric mirror **58** (**FIGS. 3** and **20**).

[135] **FIG. 21** is an overlay of the available scanning area **320** of the exit-pupil expander **52** (**FIG. 3**), an image **322** that the beam **60** (**FIG. 3**) scans onto the area **320**, and a distorted image **324** as perceived by an operator (not shown in **FIG. 20**) whose eyes are within the viewing space **30** (**FIG. 2**) according to an embodiment of the invention — the area **320** and the images **322** and **324** may not be drawn to scale. The image **322** is rectangular, has a width p , and is centered within the scanning area **320** of the exit-pupil expander **52**.

[136] With no distortion, the perceived image **324** would typically have the same shape, orientation, and relative location as the scanned image **322**. Note that the apertures of the expanded beam **78** and the beamlets **32** (**FIG. 2**) have no affect on the shape of the scanned image **322**; consequently, the heads-up display **40** can simultaneously generate the expanded beam and beamlets having hexagonal apertures and the image **322** having a rectangular shape. But the shape of the perceived image **324** is affected by distortion to the apertures of the expanded beam **78** and beamlets **32** as discussed below.

[137] In this example, however, distortion causes the perceived image **324** to differ from the scanned image **322** in shape (trapezoidal vs. rectangular caused by a taper of β in the width p), orientation (rotated counterclockwise by $\alpha = 45^\circ$ relative to the scanned image), and relative location (the center of the perceived image is shifted left a relative distance q from the center of the scanned image). More specifically, this distortion introduces an undesired taper β to the apertures of the expanded beam **78** (this component of the distortion is often called “key stoning”), rotates the aperture of the expanded beam counterclockwise 45° from its desired orientation, and shifts the aperture of the expanded beam left from its desired location by a relative distance q . Such distortion is often caused by an optical mismatch between the wind screen **42** (**FIG. 3**) and the aspheric mirror **58** (**FIGS. 3** and **20**), although this distortion may

have other causes. Typically, such distortion may exist when the vehicle (not shown in **FIG. 21**) incorporating the windscreen **42** (**FIG. 3**) is first assembled, or when the wind screen is replaced.

[138] Still referring to **FIG. 21**, where the distortion in the perceived image
5 **324** is caused by an optical mismatch between the wind screen **42** (**FIG. 3**) and aspheric mirror **58** (**FIGS. 3** and **20**), a conventional solution is to replace either the wind screen or the aspheric mirror or to modify the curvature of the mirror to obtain a better optical match with the windscreen. But because this solution requires replacement or modification of components and the calculation of the
10 curvature of at least one of the wind screen **42** and mirror **58**, this solution is often relatively time consuming and expensive.

[139] But as discussed below, one can electronically calibrate or recalibrate the heads-up display **40** (**FIG. 3**) to compensate for such distortion according to an embodiment of the invention. Therefore, one can reduce or
15 eliminate the distortion without replacing or modifying components or otherwise changing the physical structure of the display **40**.

[140] **FIG. 22** is an overlay of the available scanning area **320** of the exit-pupil expander **52** (**FIG. 3**), an image **330** that the beam **60** (**FIG. 3**) scans onto the area **320** and that is operable to counteract distortion, and a
20 distortion-compensated image **332** that is perceived as being substantially distortion free by an operator (not shown in **FIG. 22**) whose eyes are within the viewing space **30** (**FIG. 2**) according to an embodiment of the invention — the area **320** and the images **330** and **332** may not be drawn to scale. As discussed further below, the shape, orientation, and taper of the distortion-counteracting
25 image **330** are the respective inverses of the shape, orientation, and taper of the distorted image **324** of **FIG. 21**.

[141] Referring to **FIGS. 21** and **22**, one can calibrate the heads-up display **40** (**FIG. 3**) to correct the distorted image **324** by programming the display to scan the distortion-counteracting image **330** onto the exit-pupil expander **52**
30 (**FIG. 3**) according to an embodiment of the invention. More specifically, one programs the beam generator **44** (**FIG. 3**) of the display **40** to effectively generate the distortion-counteracting image **332** from the original scanned image **322** by

shifting the original image a distance q to the right (*i.e.*, a distance $-q$ to the left), rotating the shifted original image by an angle $-\alpha$, and tapering the sides of the shifted and rotated original image by an angle $-\beta$. The programmed image electronics **62** (**FIG. 3**) perform this shifting, rotating, and tapering by modulating the beam sources **64**, **66**, and **68** (**FIG. 3**) in an appropriate manner. To allow this shifting, rotating, and tapering, the area **320** of the exit-pupil expander **52** is larger, for example 15% larger, than the area of the original image **322**.

[142] Consequently, the same distortion that transformed the original scanned image **322** into the distorted image **324** now transforms the distortion-counteracting image **330** into the distortion-compensated image **332**, which the operator perceives as being undistorted, *i.e.*, as having the same relative, location, orientation, and shape as the original scanned image **322**.

[143] Because one can calibrate the heads-up display **40** by programming instead of physical modification, he can often perform such calibration more quickly and cheaply than he can perform a conventional calibration. Furthermore, one can automate the calibration by programming a test/calibration machine (not shown in **FIGS. 21** and **22**) to capture the distorted image **324**, to calculate the parameters (*e.g.*, shape, orientation, relative location) of the distortion-counteracting image **330** from the captured image, and to program the beam generator **44** for modulating the output beam **60** so that the scanner **44** scans the distortion-counteracting image onto the available area **320** of the exit-pupil expander **52** (beam generator, output beam, scanner, and exit-pupil expander shown in **FIG. 3**).

[144] Still referring to **FIGS. 21** and **22**, other embodiments of the above-described distortion-calibration technique are contemplated. For example, one can program the beam generator **44** (**FIG. 3**) to correct distortions other than shift, rotational, and tapering distortions. For example, one can program the generator **44** to correct non-taper distortions to the shape of the image. Furthermore, one can program the beam generator **44** to modulate the intensity of the output beam **60** to correct distortions in the intensity profile of the expanded beam **78**.

[145] From the foregoing it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the invention. For example, referring to **FIGS. 3, 21, and 22**, the
5 heads-up display **40** may scan an image onto the exit-pupil expander **52** using a tiling technique. That is, the display **40** can generate multiple beams **60** such that the scanner **46** sweeps multiple beams, each beam scanning a different portion of the image onto the exit-pupil expander **57**. Tiling is discussed in U.S. patent application Serial No. 09/858,287 filed May 15, 2001, U.S. Patent application
10 Serial No. 09/858,688 filed May 15, 2001, U.S. Patent No. 6,755,536 issued on June 29, 2004, and U.S. Patent No. 6,639,719 issued on October 28, 2003, which are incorporated by reference.

WHAT IS CLAIMED IS:

1. A heads-up display, comprising:
 - a scanner assembly operable to generate an image by sweeping a beam of electromagnetic energy in at least one dimension; and
 - 5 a projection assembly operable to direct the image into a predetermined viewing space having a substantially uniform intensity profile in a cross section having a region that is substantially normal to a viewing dimension.
2. The heads-up display of claim 1 wherein a brightest region of the profile in the cross section across a first measurement aperture of not greater
10 than approximately 8 millimeters differs from a dimmest region of the profile in the cross section across a second measurement aperture of not greater than approximately 8 millimeters by no more than approximately $\pm 11\%$.
3. The heads-up display of claim 2 wherein the first and second measurement apertures are each no greater than approximately 1 millimeters.
- 15 4. The heads-up display of claim 1 wherein:
 - the projection assembly comprises an exit-pupil expander; and
 - the scanner is operable to generate the image by sweeping the beam in two dimensions onto the exit-pupil expander.
5. The heads-up display of claim 1 wherein a planar projection of the
20 cross section of the viewing space has a hexagonal shape.
6. The heads-up display of claim 1 wherein a planar projection of the cross section of the viewing space has an elongated hexagonal shape.
7. The heads-up display of claim 1 wherein the cross section of the viewing space is a planar cross section.
- 25 8. The heads-up display of claim 1 wherein a planar projection of the cross section of the viewing space has one dimension of at least 100 millimeters.
9. The heads-up display of claim 1 wherein:
 - the projection assembly is further operable to generate beamlets within the viewing space; and
 - 30 a difference in the intensity profile over a measurement aperture of at least a portion of the viewing space is no greater than approximately $\pm 2\%$, the measurement aperture being no greater than approximately 8 millimeters.

10. The heads-up display of claim 9 wherein the measurement aperture is no greater than approximately 1 millimeters.

11. A method, comprising:

sweeping a beam of light in at least one dimension to generate an image;

5 and

directing the image into a predetermined viewing space having a substantially uniform intensity envelope in a cross section having a region that is substantially normal to a viewing dimension.

12. The method of claim 11 wherein directing the image comprises
10 generating a plurality of beamlets within the viewing space.

13. The method of claim 11 wherein:

a planar projection of the cross section has a predetermined shape; and

directing the image comprises generating within the viewing space a
plurality of beamlets each having a planar cross section with substantially the
15 predetermined shape.

14. A scanned-beam display, comprising:

a beam generator operable to generate an output beam of electromagnetic
energy having a substantially uniform intensity profile in a planar cross section
that is normal to a direction in which the output beam propagates; and

20 a beam scanner operable to generate an image by sweeping the output
beam in at least one dimension.

15. The scanned-beam display of claim 14 wherein the beam generator
comprises:

a beam source operable to generate an input beam having a non-uniform
25 intensity profile in a planar cross section that is normal to a direction in which the
input beam propagates; and

a beam conditioner operable to convert the input beam into the output
beam.

16. The scanned-beam display of claim 14 wherein the beam generator
30 comprises:

a beam source operable to generate an input beam having a non-uniform
intensity profile in a planar cross section that is normal to a direction in which the
input beam propagates; and

a top-hat converter operable to convert the input beam into the output beam.

17. The scanned-beam display of claim 14 wherein the beam generator comprises:

5 a beam source operable to generate an input beam having a non-uniform intensity profile in a planar cross section that is normal to a direction in which the input beam propagates; and

a clipping aperture operable to block an outer portion of the input beam and to generate the output beam from a passed inner portion of the input beam.

10 18. The scanned-beam display of claim 14 wherein the beam generator comprises:

a beam source operable to generate an input beam having a substantially Gaussian intensity profile in a planar cross section that is normal to a direction in which the input beam propagates; and

15 a beam conditioner operable to convert the input beam into the output beam by converting the substantially Gaussian intensity profile into the substantially uniform intensity profile.

19. The scanned-beam display of claim 14 wherein a brightest region of the output beam in the cross section differs from a dimmest region of the output beam in the cross section by no more than +/- 10%.

20 20. The scanned-beam display of claim 14 wherein the output beam comprises visible light.

21. A method, comprising:

25 generating an output beam of electromagnetic energy having a substantially uniform intensity profile in a planar cross section that is normal to a direction in which the output beam propagates; and sweeping the output beam in at least one dimension to generate an image.

22. The method of claim 21 wherein generating the output beam comprises:

30 generating an input beam having a non-uniform intensity profile in a planar cross section that is normal to a direction in which the input beam propagates; and

passing the input beam through a top-hat converter to generate the output beam.

23. The method of claim 21 wherein generating the output beam comprises:

5 generating an input beam having a substantially Gaussian intensity profile in a planar cross section that is normal to a direction in which the input beam propagates; and

clipping an outer portion of the input beam; and

10 generating the output beam from an unclipped inner portion of the input beam.

24. A heads-up display, comprising:

a beam generator operable to generate a beam of electromagnetic energy;

and

15 a micro-electro-mechanical scanner operable to generate an image by sweeping the beam in at least one dimension.

25. The heads-up display of claim 24 wherein the scanner is operable to generate an image by resonantly sweeping the beam in a first dimension and by linearly sweeping the beam a second dimension that is substantially perpendicular to the first dimension.

20 26. A heads-up display, comprising:

a beam generator operable to generate a beam of electromagnetic energy;

and

a scanner operable to generate an image by resonantly sweeping the beam in at least one dimension.

25 27. A method, comprising:

generating a beam of electromagnetic energy; and

resonantly sweeping the beam in one dimension to generate a virtual image that is reflected from a wind screen of a vehicle.

28. The method of claim 27 wherein resonantly sweeping the beam
30 comprises generating the image while resonantly sweeping the beam in both directions of the dimension.

29. A heads-up display, comprising:

a scanner operable to generate an image by sweeping a beam of electromagnetic energy in at least one dimension; and

a projection assembly that includes a first microlens array operable to direct the image into a predetermined viewing space.

5 30. The heads-up display of claim 29 wherein the first microlens array comprises a varying-phase microlens array.

 31. The heads-up display of claim 29 wherein the first microlens array comprises lenslets, one of the lenslets having a first value for a lenslet property and another of the lenslets having a second value for the lenslet property.

10 32. The heads-up display of claim 29 wherein the projection assembly comprises a second microlens array disposed adjacent to the first microlens array such that the first and second microlens arrays are together operable to direct the image into the predetermined viewing space.

 33. The heads-up display of claim 29 wherein:
15 the first microlens array has a focal plane and a focal length from the focal plane; and

 the projection assembly further includes a second microlens array having a focal plane and the focal length from the focal plane, the focal plane of the second microlens array being substantially parallel to and spaced the focal length
20 from the focal plane of the first microlens array.

 34. The heads-up display of claim 29 wherein the first microlens array comprises lenslets arranged in a pattern and is operable to cause a planar projection of the cross section of the viewing space to have the pattern.

 35. The heads-up display of claim 29 wherein the first microlens array
25 comprises lenslets arranged in an elongated hexagonal pattern and is operable to cause a planar projection of the cross section of the viewing space to have the elongated hexagonal pattern.

 36. A method, comprising:
 sweeping a beam having a profile in a cross section;
30 converting the profile of the beam into substantially a spatial sinc function;
 performing a spatial Fourier Transform on the spatial sinc function to generate an image; and

directing the image into a predetermined viewing space with a wind screen of a vehicle.

37. The method of claim 36 wherein converting the profile of the beam comprises converting the profile of the beam into substantially a spatial sinc
5 function using a dual-microlens array.

38. A scanned-beam display, comprising:
a beam generator operable to generate an output beam of electromagnetic energy having a substantially hexagonal planar cross section that is normal to a direction in which the output beam propagates; and
10 a beam scanner operable to generate an image by sweeping the output beam in at least one dimension.

39. The scanned-beam display of claim 38 wherein the beam generator comprises:
a beam source operable to generate an input beam having a
15 non-hexagonal planar cross section that is normal to a direction in which the input beam propagates; and
a clipping aperture operable to convert the input beam into the output beam.

40. The scanned-beam display of claim 38 wherein the beam generator
20 comprises:
a beam source operable to generate an input beam having a substantially circular planar cross section that is normal to a direction in which the input beam propagates; and
a clipping aperture operable to convert the input beam into the output
25 beam by converting the substantially circular cross section into the substantially hexagonal cross section.

41. The scanned-beam display of claim 38 wherein the cross section of the output beam has a substantially elongated hexagonal shape.

42. A method, comprising:
30 generating an output beam of electromagnetic energy having a substantially hexagonally shaped planar cross section that is normal to a direction in which the output beam propagates; and
sweeping the output beam in at least one dimension to generate an image.

43. The method of claim 42, further comprising:
forming beamlets of the image, each beamlet having a substantially hexagonally shaped planar cross section that is normal to a direction in which the beamlet propagates; and
5 directing the beamlets into a predetermined viewing space.
44. A heads-up display, comprising:
a scanner operable to generate an image by sweeping a beam of electromagnetic energy in at least one dimension; and
a projection assembly having a mirror operable to reflect the image off of a
10 wind screen and into a predetermined viewing space having a cross section, the mirror operable to maintain a dimension of the cross section at a substantially constant size for reflection of the image off of a predetermined region of the windshield.
45. The heads-up display of claim 44 wherein the mirror is operable to
15 move the viewing space in a dimension substantially parallel to the cross section.
46. The heads-up display of claim 44 wherein the mirror is operable to move the viewing space in a dimension substantially normal to the cross section.
47. A heads-up display, comprising:
a scanner operable to generate an image by sweeping a beam of
20 electromagnetic energy in at least one dimension; and
a projection assembly having a mirror operable to reflect the image off of a wind screen and into a predetermined viewing space having a cross section, the mirror operable to move the viewing space in a dimension substantially normal to the cross section.
- 25 48. A method, comprising:
sweeping a beam of electromagnetic energy in at least one dimension to generate an image; and
reflecting the image off of a wind screen and into a predetermined viewing space having a cross section such that a dimension of the cross section is
30 maintained at a substantially constant size for reflection of the image off of a predetermined region of the wind screen.
49. A heads-up display, comprising:

a scanner operable to generate an image by sweeping a beam of electromagnetic energy in at least one dimension; and

5 a projection assembly operable to direct the image into a predetermined viewing space such that in a cross section of the viewing space having a region that is substantially normal to a viewing dimension, the image has a substantially uniform intensity profile.

10 50. The heads-up display of claim 49, further comprising a beam generator operable to generate the beam of electromagnetic energy having a substantially uniform intensity profile in a planar cross section that is normal to a direction in which the beam propagates.

51. The heads-up display of claim 49, further comprising:
a beam generator operable to generate the beam of electromagnetic energy having a hexagonal aperture and a substantially uniform intensity profile in a planar cross section that is normal to a direction in which the beam propagates;
15 and

wherein the cross section of the viewing space has a hexagonal shape.

52. The heads-up display of claim 49, further comprising:
a beam generator operable to generate the beam of electromagnetic energy having a hexagonal aperture and a substantially uniform intensity profile in
20 a planar cross section that is normal to a direction in which the beam propagates;
wherein the cross section of the viewing space has a hexagonal shape;
and

25 wherein the viewing space includes beamlets each having a hexagonal aperture and a substantially uniform intensity profile in a planar cross section that is substantially parallel to the planar cross section of the viewing space.

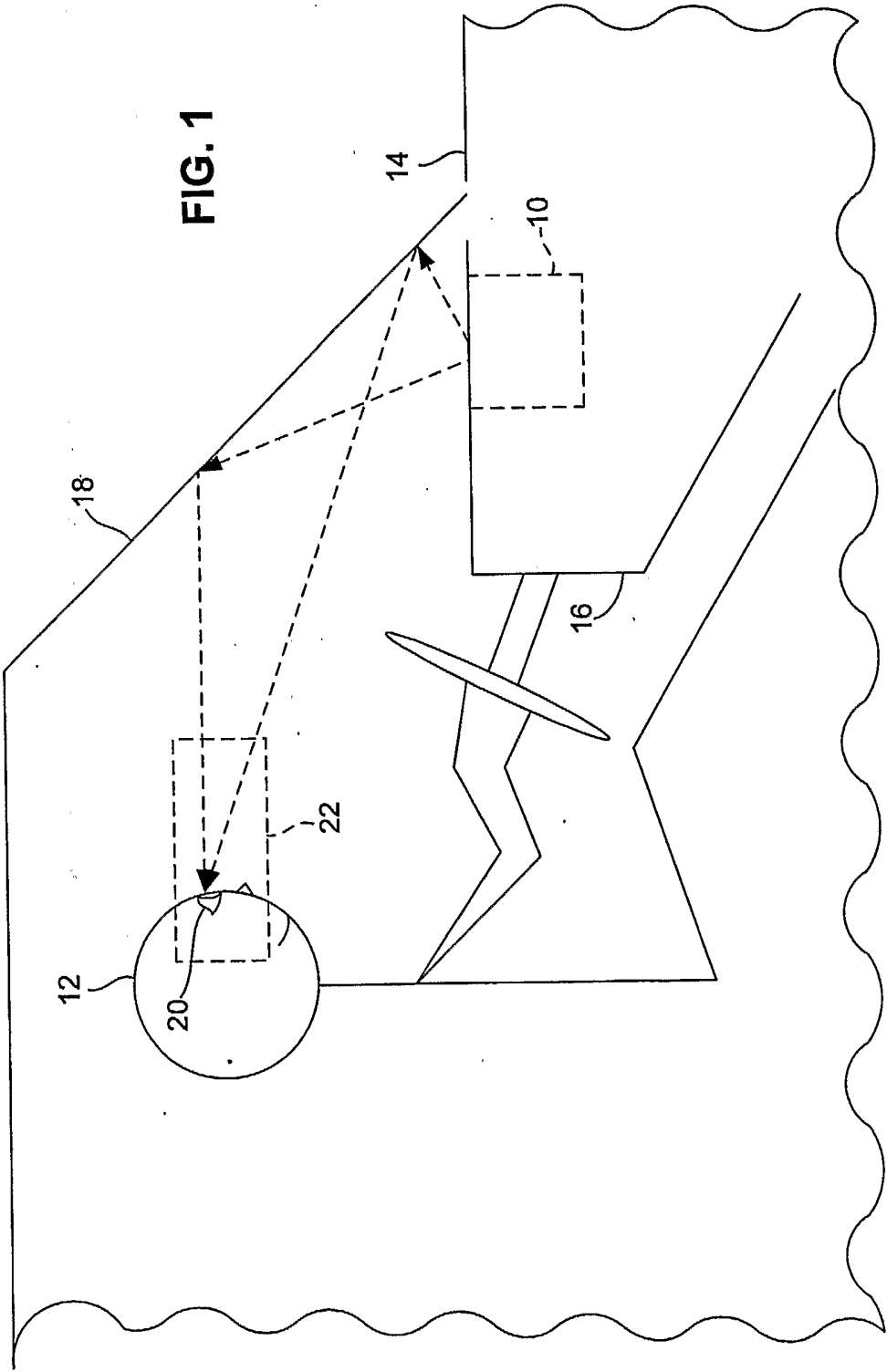
53. A method, comprising:
generating an image by sweeping a beam of electromagnetic energy in at least one dimension; and
directing the image into a predetermined viewing space such that in a cross
30 section of the viewing space having a region that is substantially normal to a viewing dimension, the image has a substantially uniform intensity profile.

54. The method of claim 53, further comprising generating the beam of electromagnetic energy having a substantially uniform intensity profile in a planar cross section that is normal to a direction in which the beam propagates.

55. The method of claim 53, further comprising:
5 generating the beam of electromagnetic energy having a hexagonal aperture and a substantially uniform intensity profile in a planar cross section that is normal to a direction in which the beam propagates; and
wherein the cross section of the viewing space has a hexagonal shape.

56. The method of claim 53, further comprising:
10 generating the beam of electromagnetic energy having a hexagonal aperture and a substantially uniform intensity profile in a planar cross section that is normal to a direction in which the beam propagates;
wherein the cross section of the viewing space has a hexagonal shape;
and

15 wherein the viewing space includes beamlets each having a hexagonal aperture and a substantially uniform intensity profile in a planar cross section that is substantially parallel to the planar cross section of the viewing space.



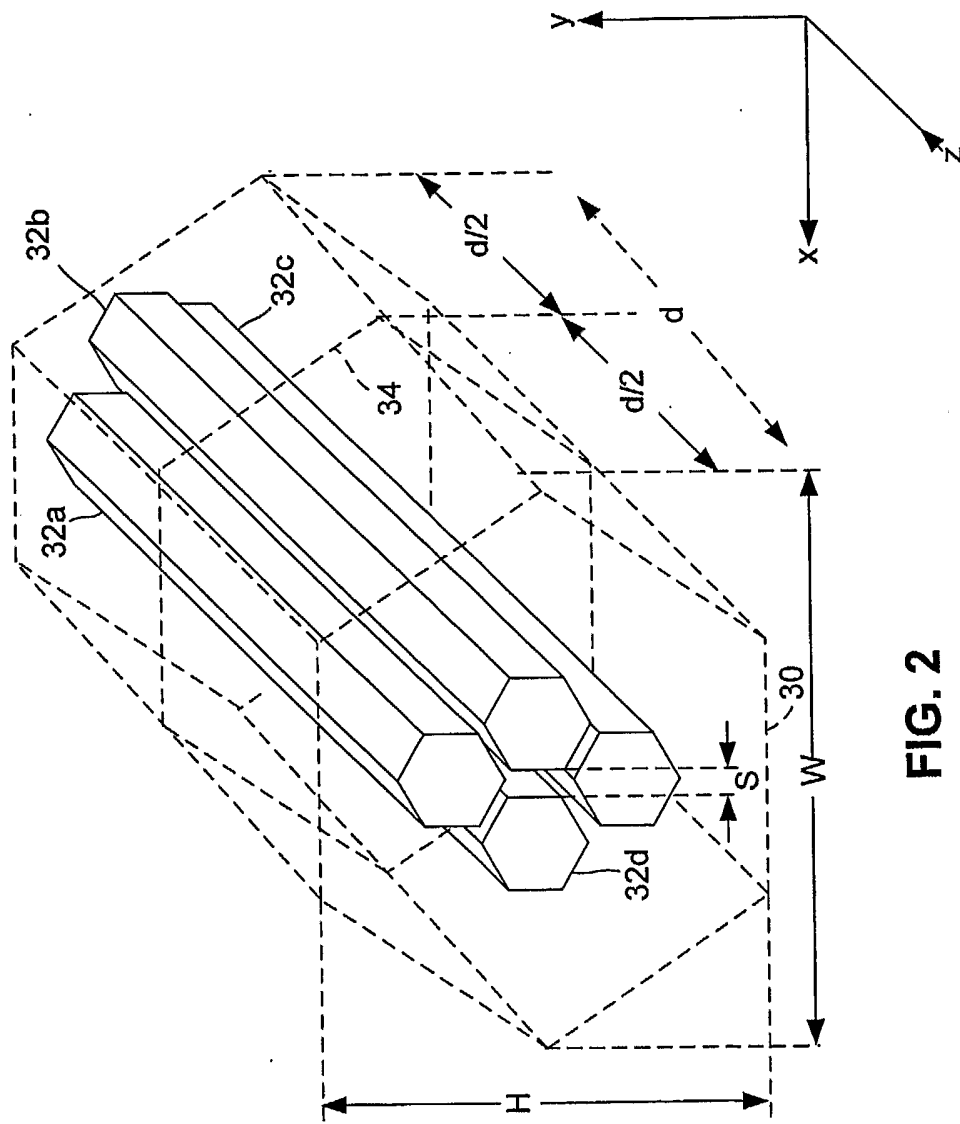
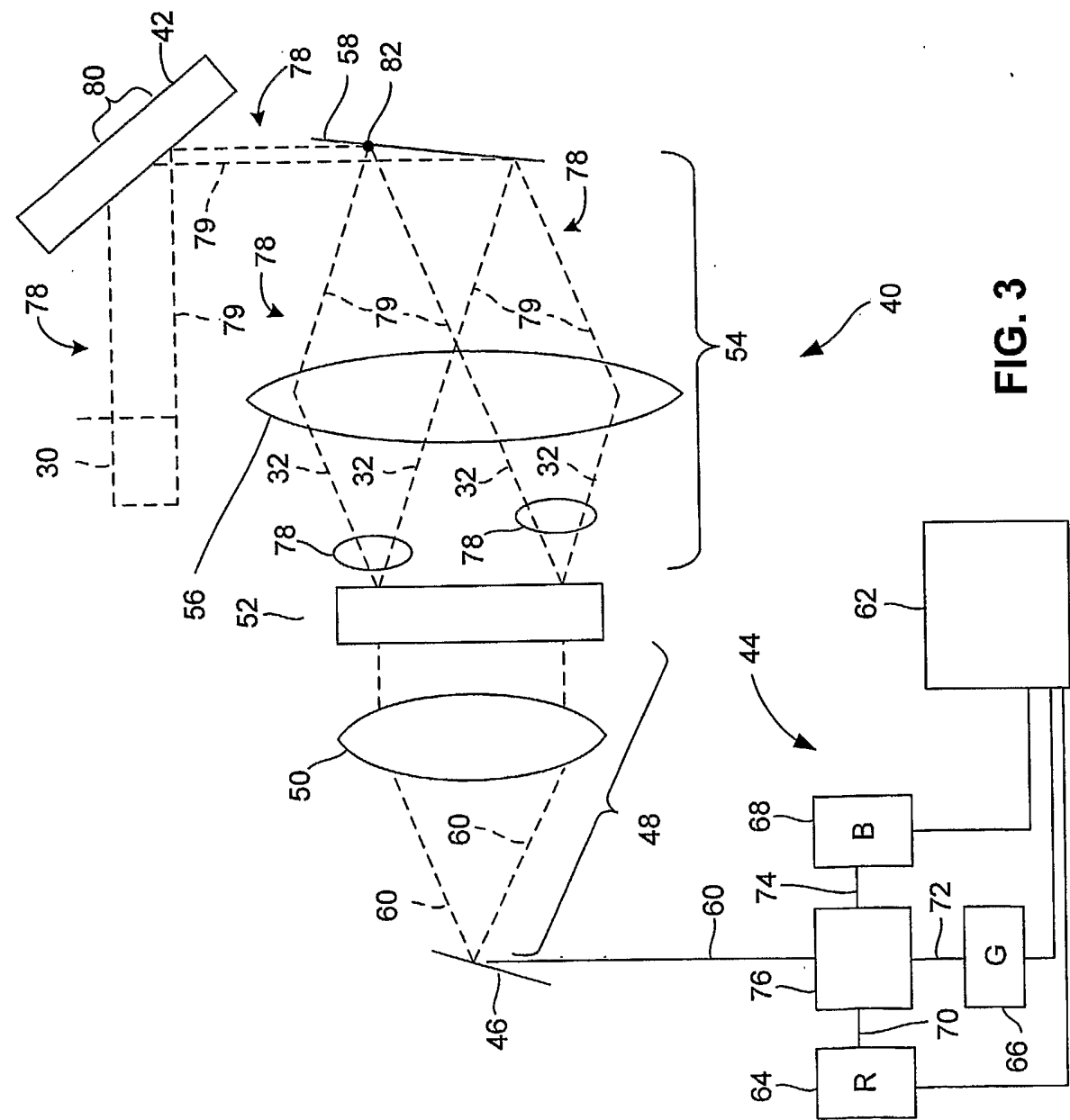
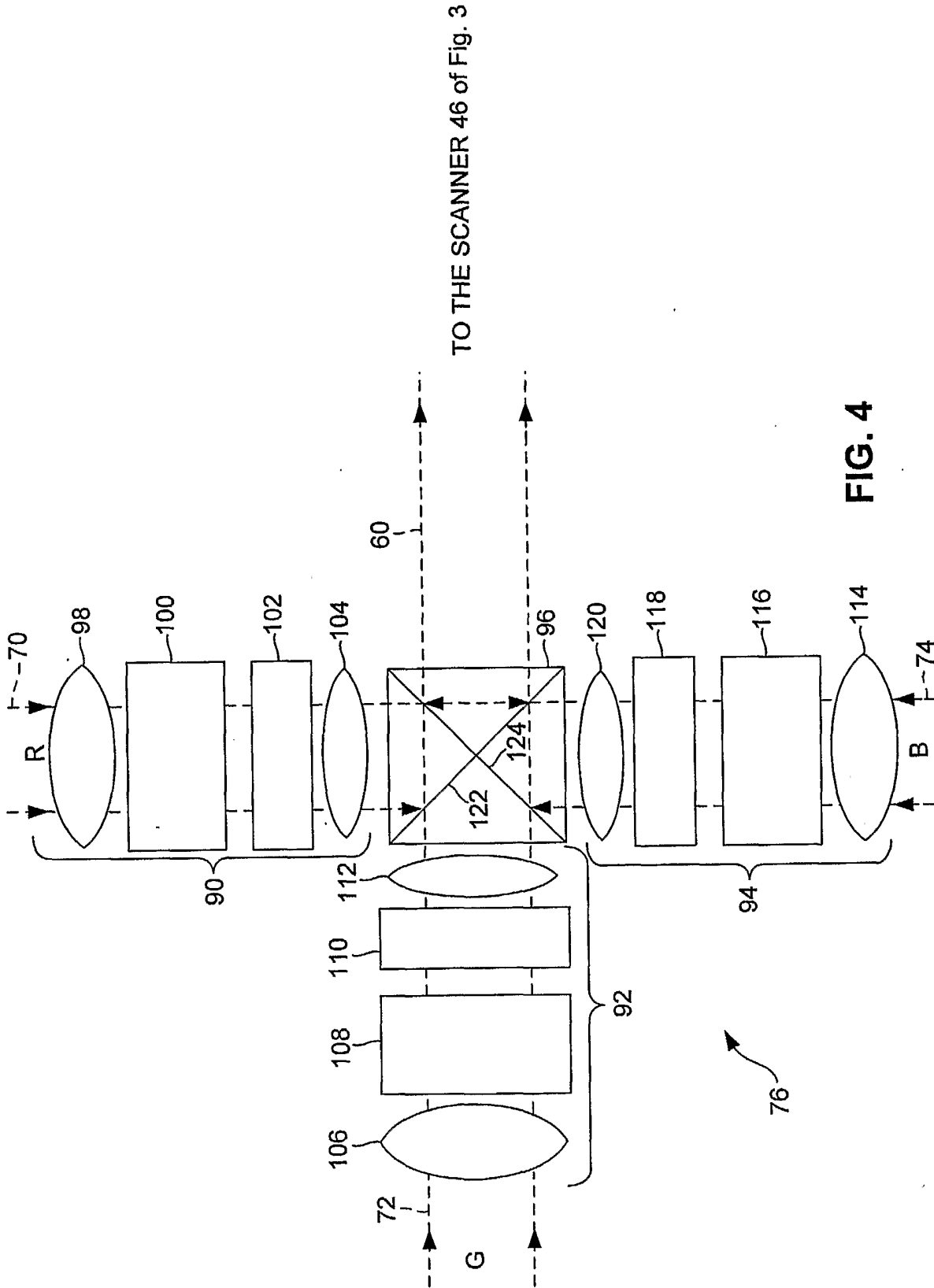


FIG. 2





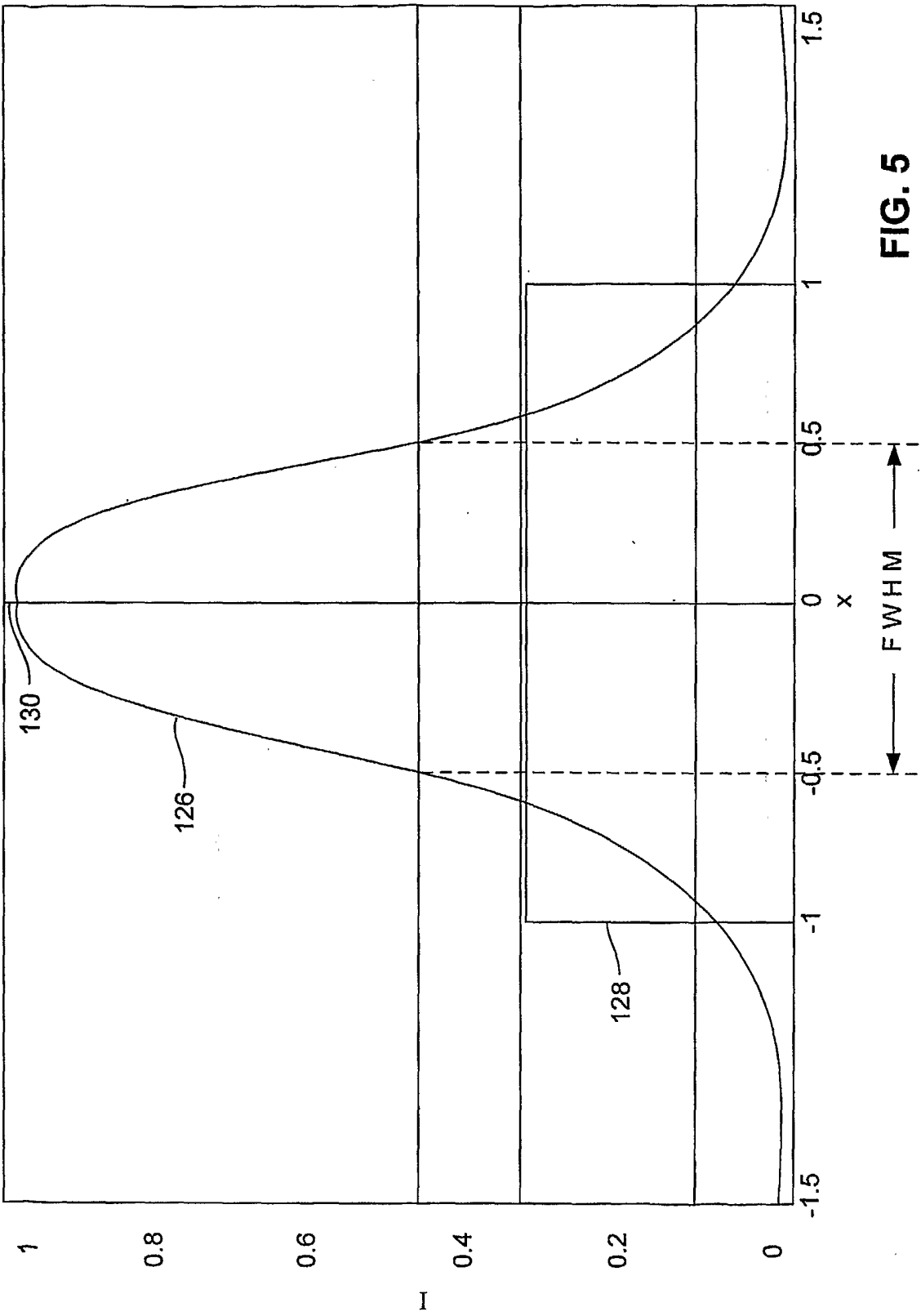


FIG. 5

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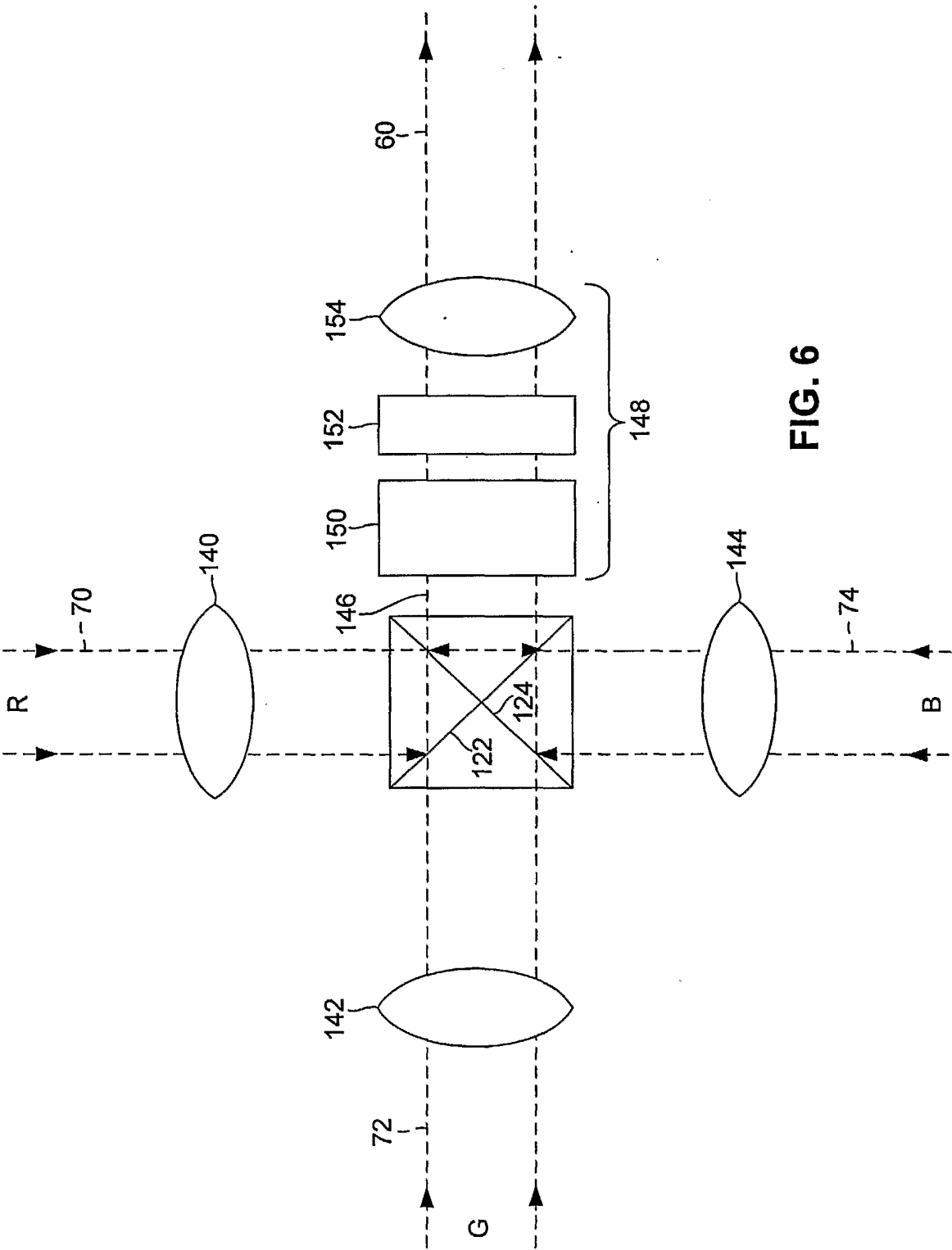


FIG. 6

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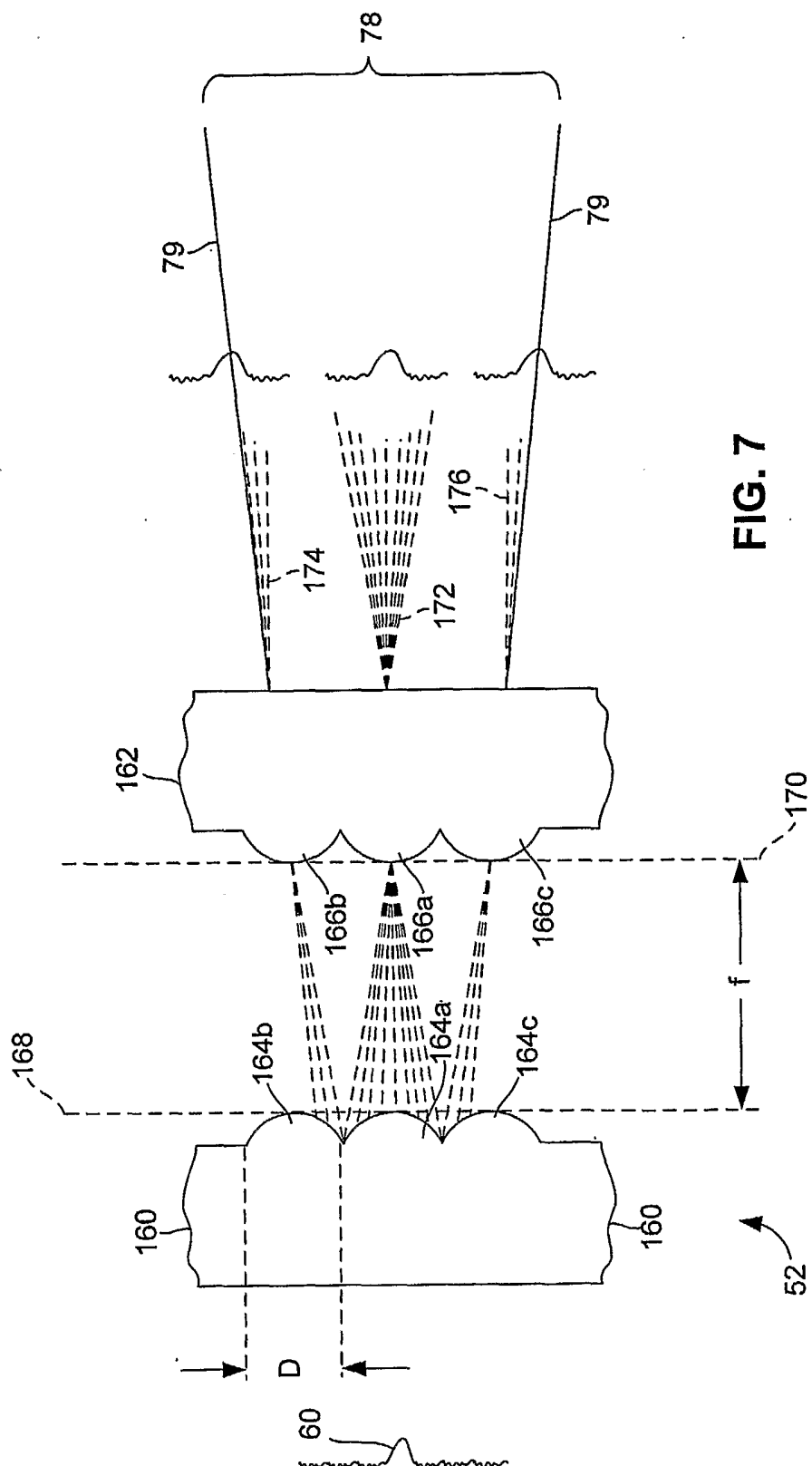


FIG. 7

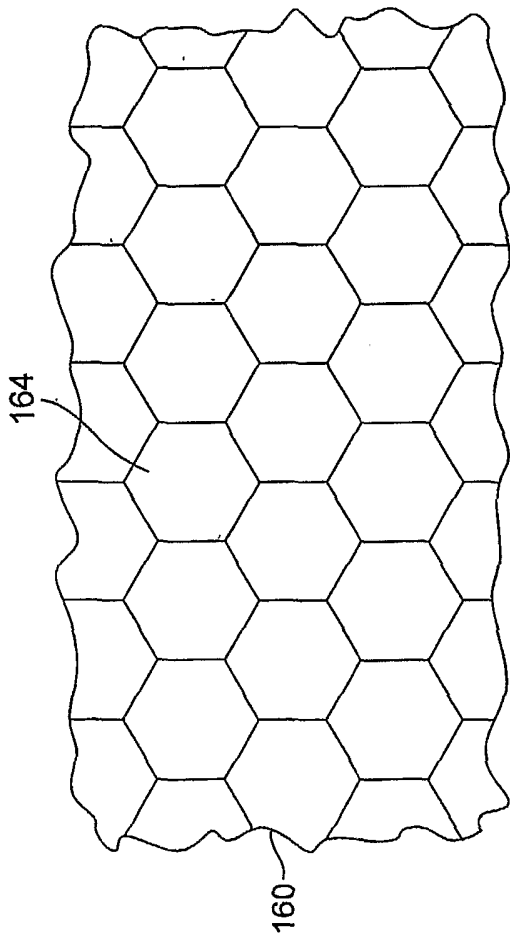


FIG. 8

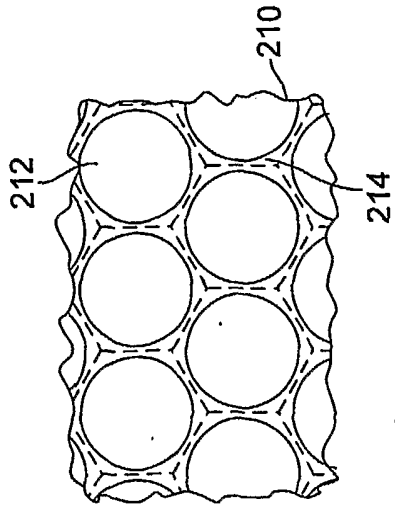


FIG. 13

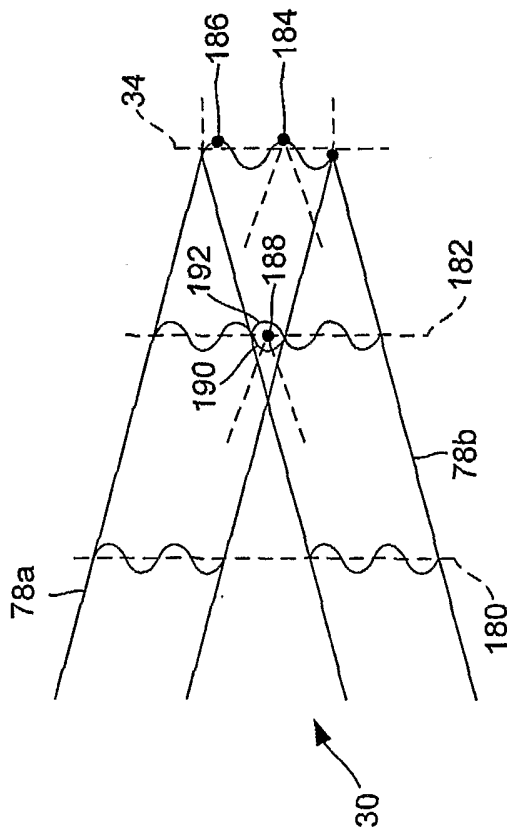


FIG. 10A

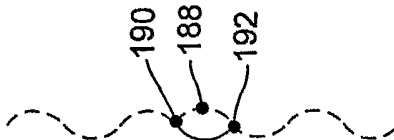


FIG. 10B

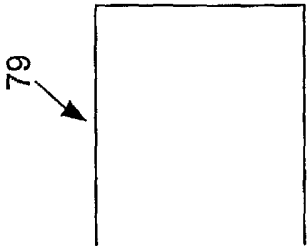


FIG. 9A

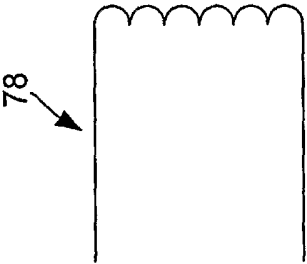


FIG. 9C

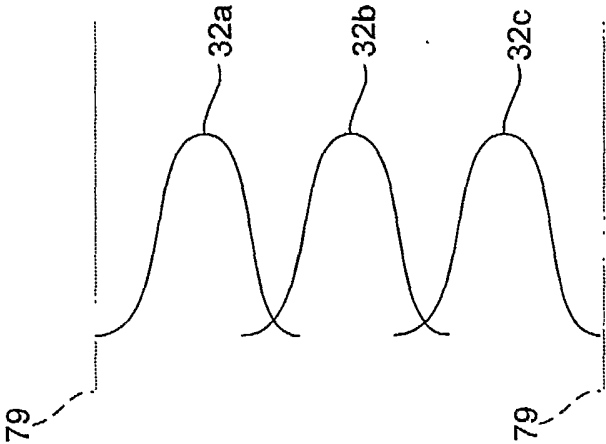


FIG. 9B

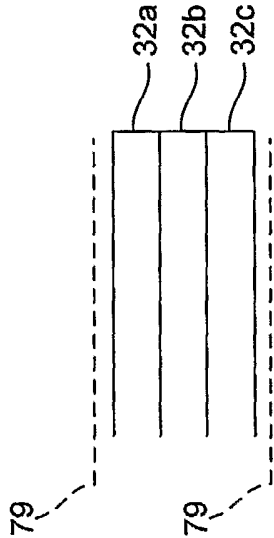


FIG. 11A

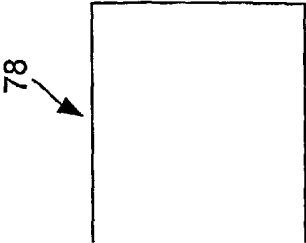


FIG. 11B

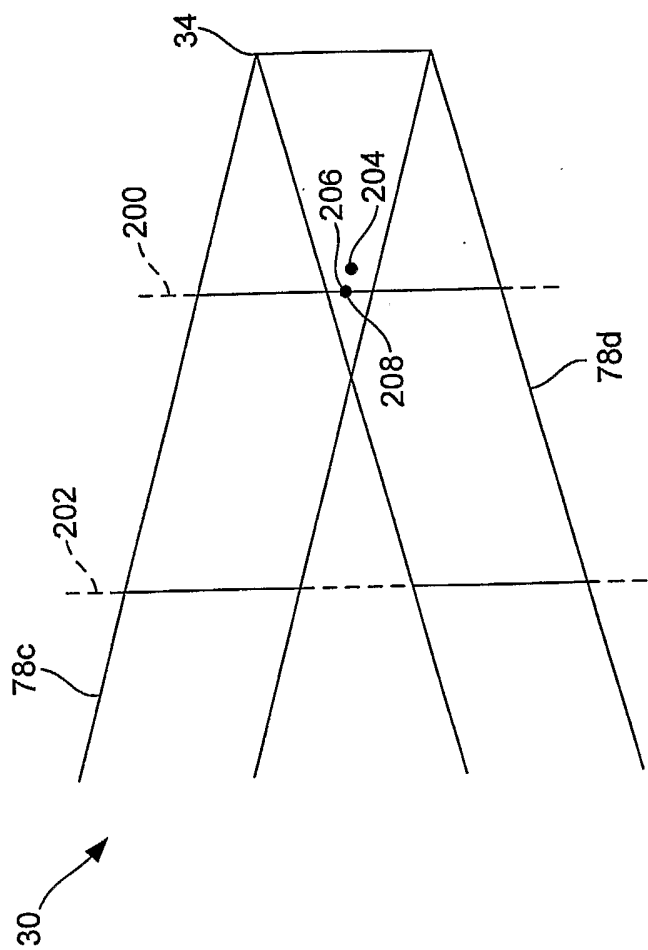
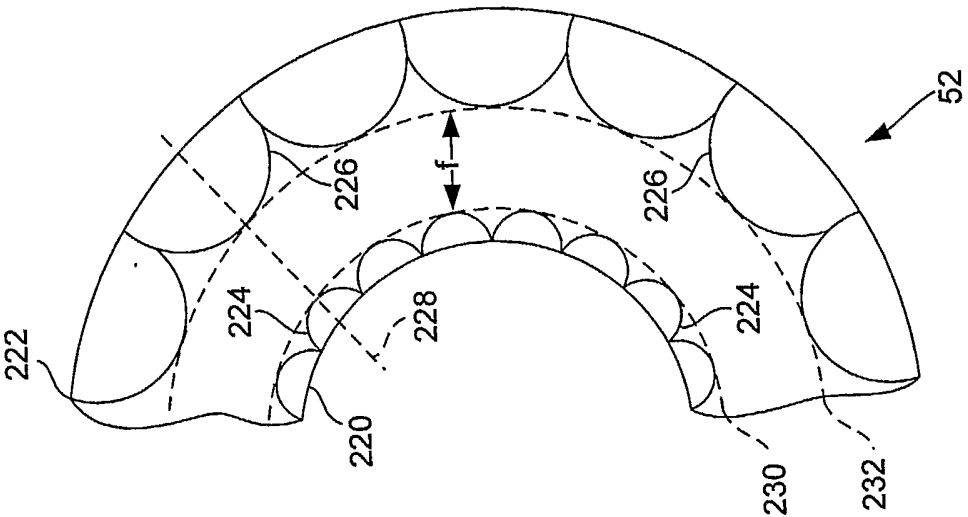
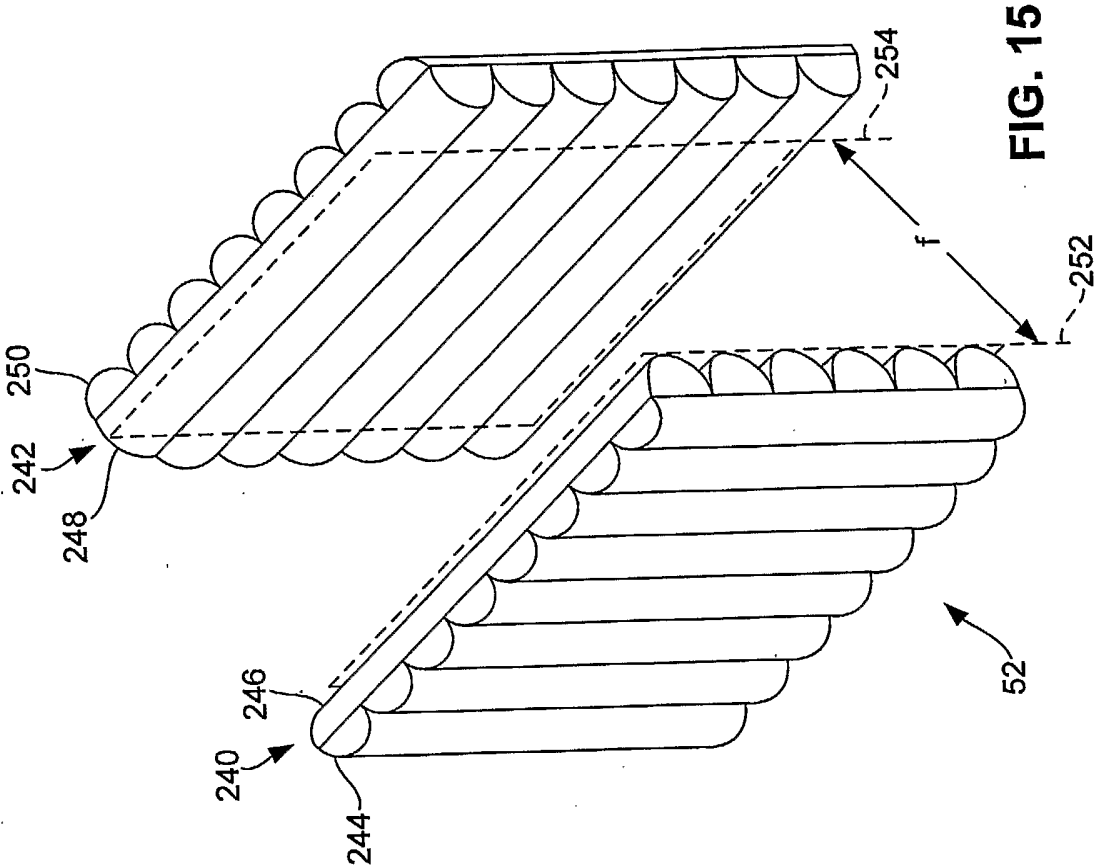
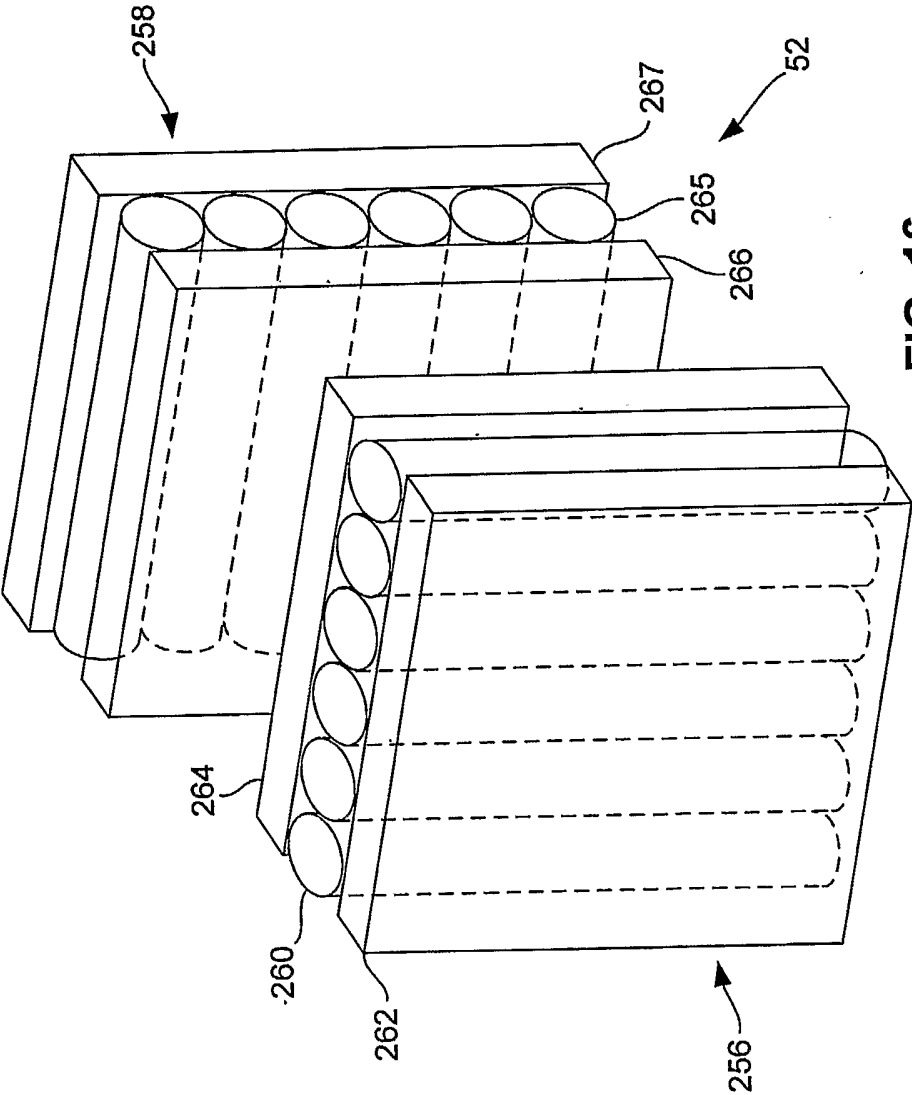
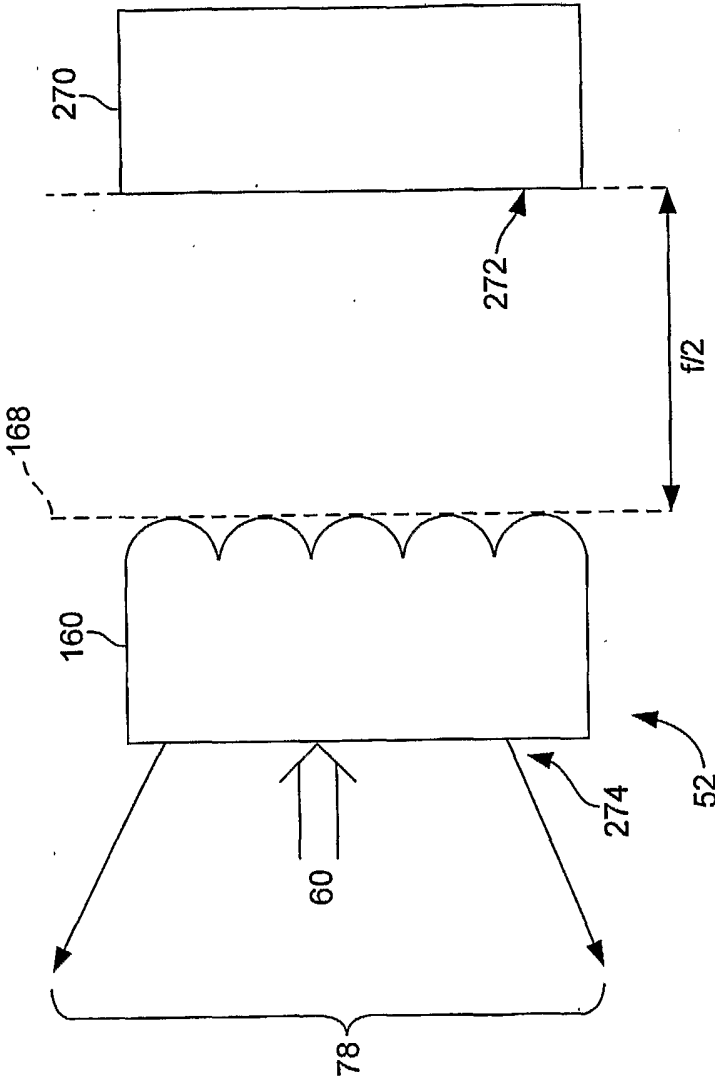


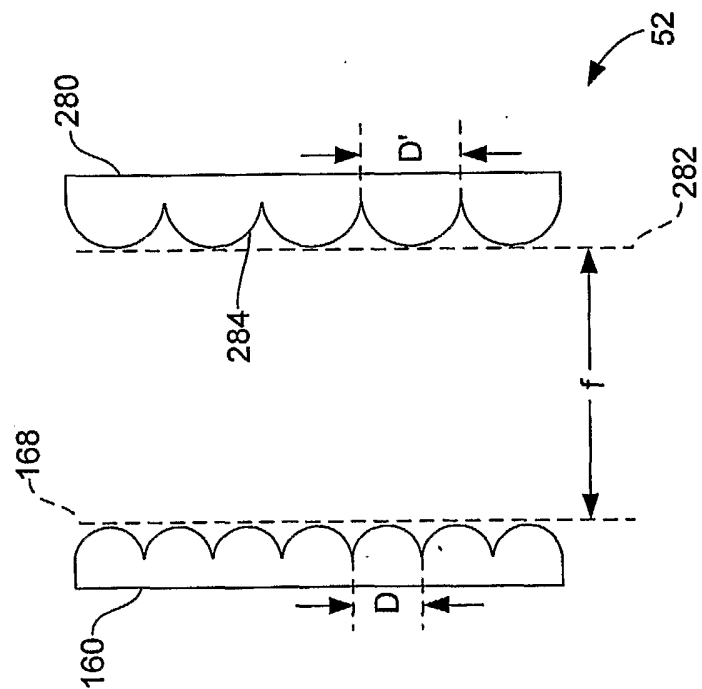
FIG. 12







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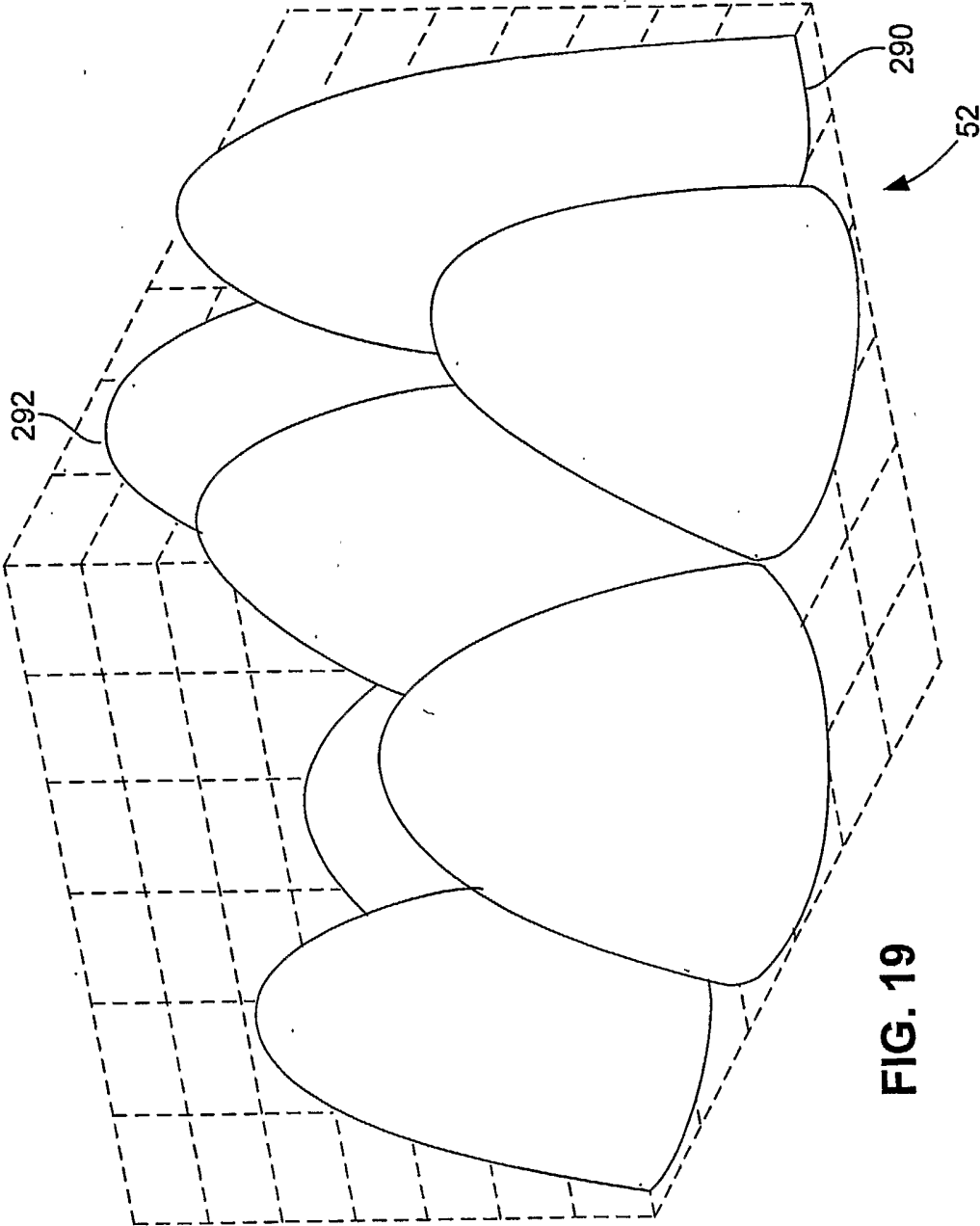
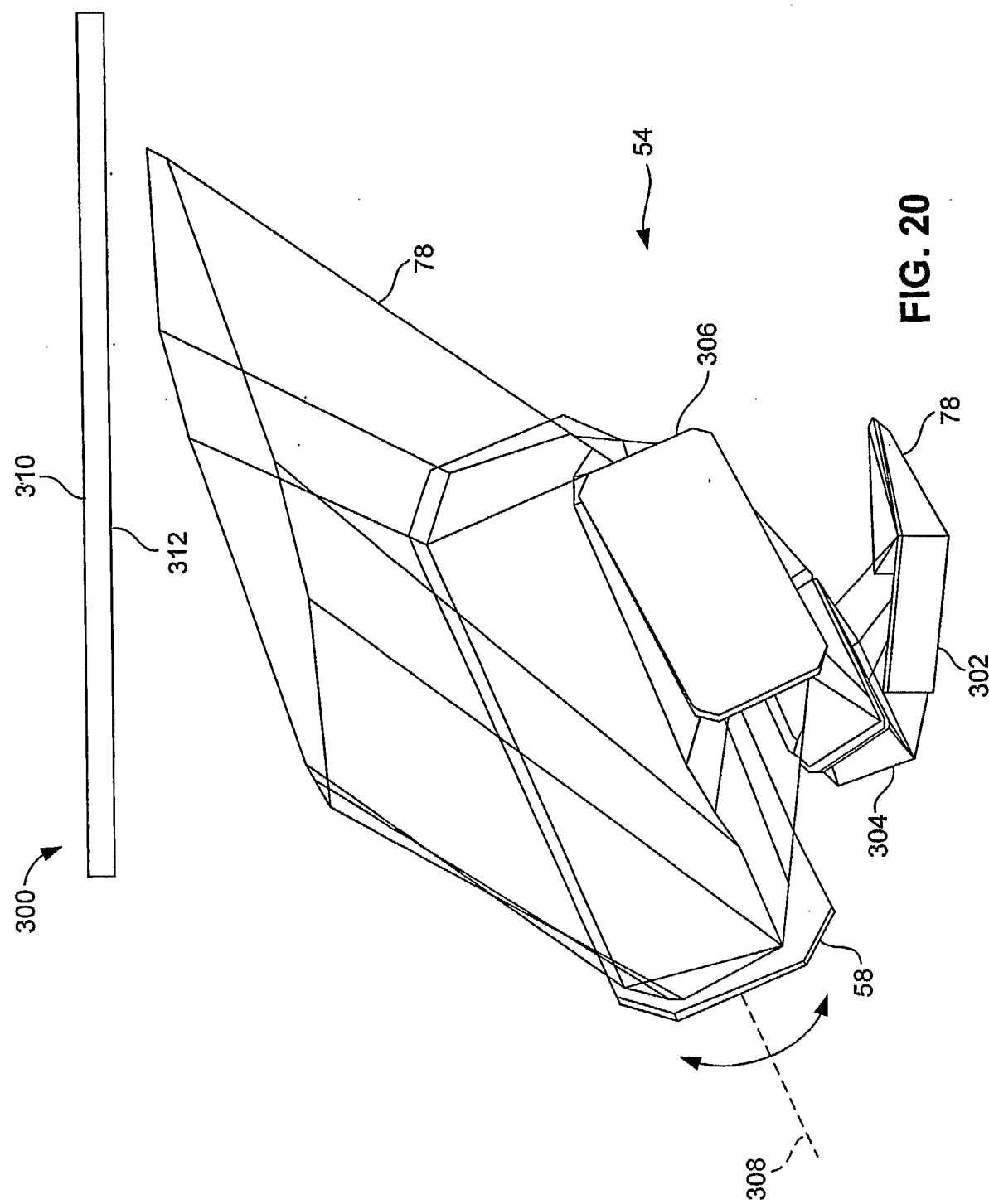


FIG. 19



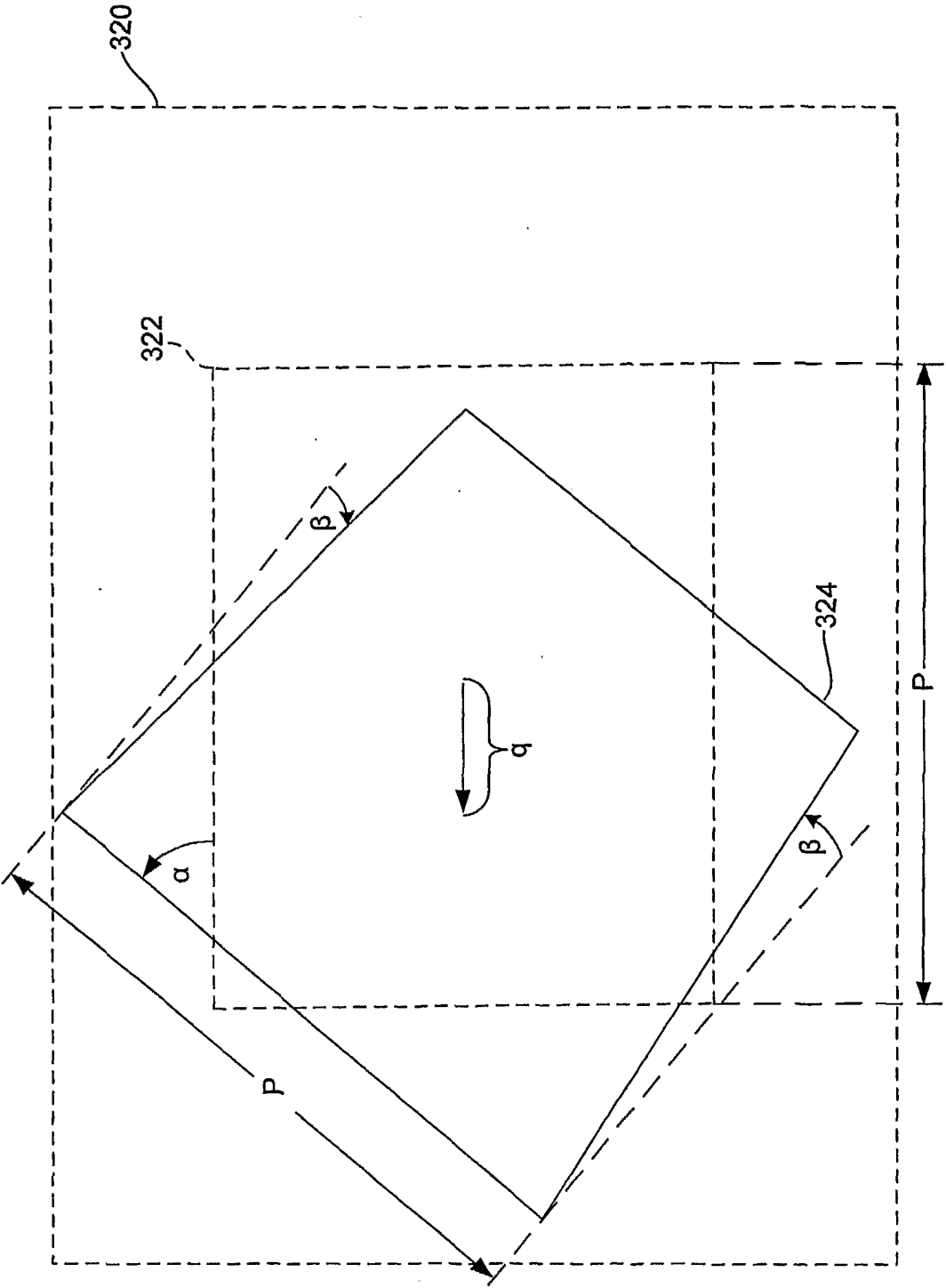


FIG. 21

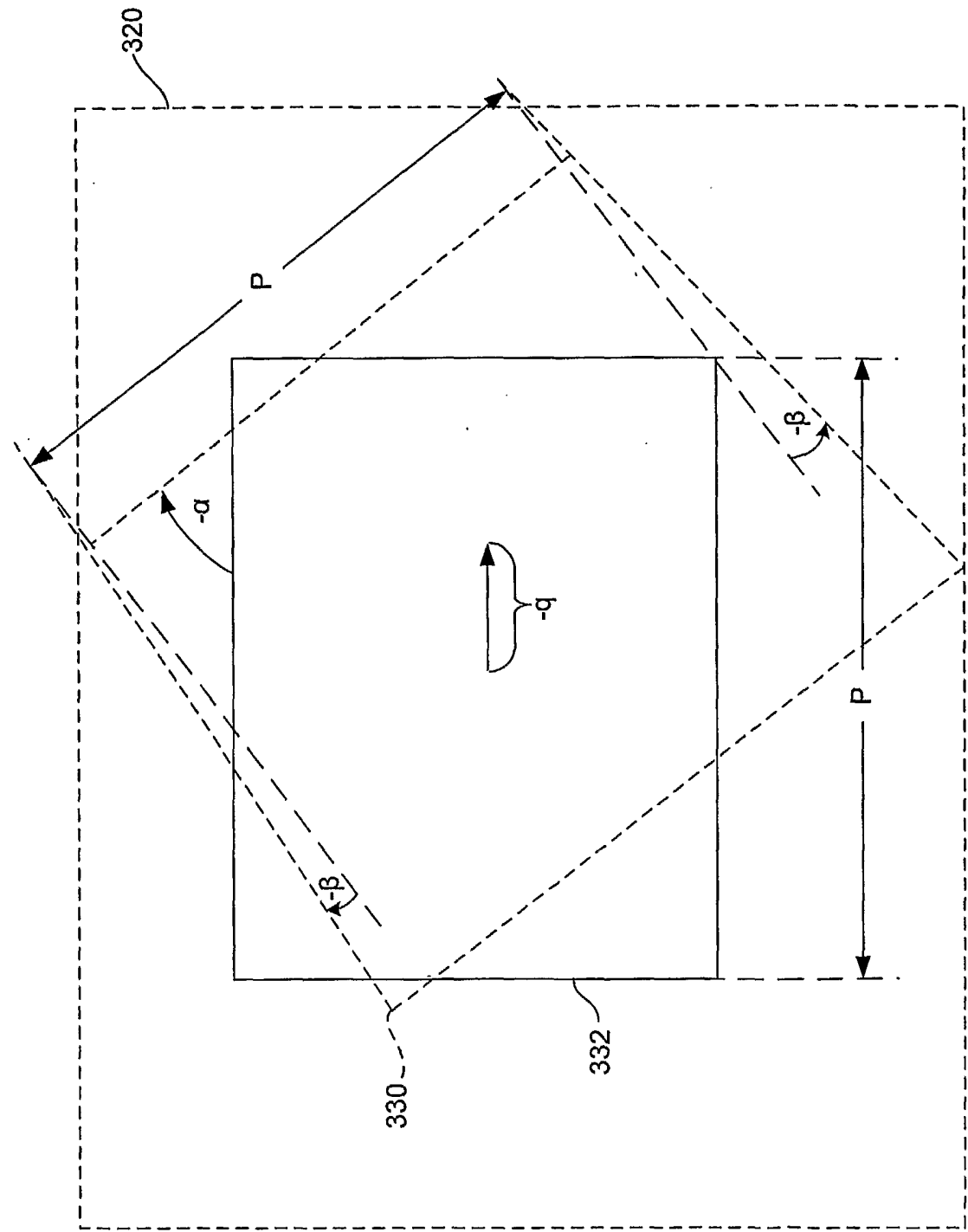


FIG. 22

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2005/003730

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B27/01

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B

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

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

EPO-Internal, COMPENDEX, INSPEC, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	POWELL KARLTON ET AL: "Exit Pupil Expander: Image Quality Performance Enhancements and Environmental Testing Results" PROC SPIE INT SOC OPT ENG; PROCEEDINGS OF SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING 2003, vol. 5079, 2003, pages 308-320, XP002327485 cited in the application *items 1-3, 6 and corresponding figures* ----- -/--	1,11,14, 21,29, 38,42, 49,53



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

* Special categories of cited documents :

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- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

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- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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- *&* document member of the same patent family

Date of the actual completion of the international search

9 May 2005

Date of mailing of the international search report

19/05/2005

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Hylla, W

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2005/003730

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	POWELL K D ET AL: "Novel approach to exit pupil expansion for wearable displays" PROCEEDINGS OF THE SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING SPIE-INT. SOC. OPT. ENG USA, vol. 4711, 2002, pages 235-248, XP002327486 ISSN: 0277-786X cited in the application * chapter 1; page 238, par.1; page 329, last but one par.; fig.15; chapter 5* -----	1,11,14, 21,29, 38,42, 49,53
X,P	UREY H ET AL: "Microlens array-based exit pupil expander for full-color display applications" PROCEEDINGS OF THE SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING SPIE-INT. SOC. OPT. ENG USA, vol. 5456, no. 1, 2004, pages 227-236, XP002327487 ISSN: 0277-786X page 227 - page 230 -----	1,11,14, 21,29, 38,42, 49,53
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A	US 5 864 432 A (DETER ET AL) 26 January 1999 (1999-01-26) abstract; figure 1 -----	1

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International Application No
PCT/US2005/003730

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