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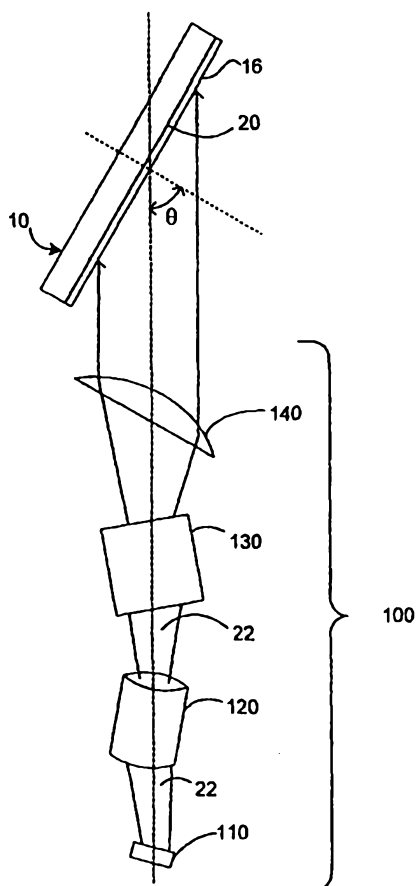
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(54) Title: OPTICAL SYSTEM FOR DISPLAY PANEL



(57) Abstract: An ultrathin panel comprised of stacking a plurality of glass sheets, which may be coated with a transparent cladding substance or may be uncoated, fastened together using an epoxy or adhesive. A coupler (16) is bonded to the inlet face (20) of the stack. A housing having a light generator (12) which is optically aligned with the coupler. The light generator is preferably placed parallel to and proximate the inlet face, thereby allowing a reduction in depth of the structure. An optical system comprises an image source (110), an imaging element (120) for creating an image of an object in an intermediate image plane, an anamorphic element (130) for reducing anamorphic distortion of the image, and a telecentric element (140) for reducing keystone-type distortion of the image.

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OPTICAL SYSTEM FOR DISPLAY PANEL

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BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to the field of display devices. In particular,
10 the present invention relates to an optical system and method for coupling an image of an
object onto a display device. More specifically, the present invention relates to an optical
system and method for coupling an image of an object onto an ultrathin planar optical display
device which is capable of reducing or eliminating distortions that typically occur when an
image is projected onto a display device which is tilted in relation to the incident image.

15

Description of the Background

Optical screens typically use cathode ray tubes (CRTs) for projecting images onto the
screen. The standard screen has a width to height ratio of 4:3 with 525 vertical lines of
resolution. An electron beam is scanned both horizontally and vertically across the screen to
20 form a number of pixels which collectively form the image.

Conventional cathode ray tubes have a practical limit in size, and are relatively deep
to accommodate the required electron gun. Larger screens are available which typically
include various forms of image projection. However, such screens have various viewing
shortcomings including limited viewing angle, resolution, brightness, and contrast, and such

screens are typically relatively cumbersome in weight and shape. Furthermore, it is desirable for screens of any size to appear black in order to improve viewing contrast. However, it is impossible for direct view CRTs to actually be black because they utilize phosphors to form images, and those phosphors are non-black.

5 Optical panels may be made by stacking optical waveguides, each waveguide having a first end and a second end, wherein an outlet face is defined by the plurality of first ends, and wherein an inlet face is defined by the plurality of second ends. Such a panel may be thin in its depth compared to its height and width, and the cladding of the waveguides may be made black to increase the black surface area, but such a panel may require expensive and
10 cumbersome projection equipment to distribute the image light across the inlet face, which equipment thereby increases the total size and cost of the panel.

 Therefore, the need exists for an optical panel which possesses the advantages corresponding to a stacked waveguide panel, but which does not require the use of expensive and cumbersome projection equipment, nor suffer from the increase in size and cost
15 necessitated by such equipment.

 In optical panels where the depth of the housing (containing the optical panel and projection equipment) is desired to be at a minimum, the projection equipment is typically positioned to accommodate these overall dimension constraints. The positioning of the projection equipment may therefore require the image path to be directed at an acute angle
20 with respect to the targeted inlet face of the panel. Thus, since the surface of the inlet face is generally highly tilted relative to the image path, an imaging system which is capable of

producing an image which is focused and is without distortions is critical. Not only is a properly focused image desired, but an image produced on the surface of the inlet face must also retain the aspect ratio of the original object while maintaining a linear point-to-point mapping of the object to the image.

5 Therefore, the need also exists for an optical system for an optical panel which is capable of producing an accurate image on a highly tilted inlet face surface relative to the image path, and which does not suffer from improperly focused images and image distortions which yield false aspect ratios of the original object and inconsistent, linear point-to-point mapping of the object to the image.

10 SUMMARY OF THE INVENTION

 The present invention is directed to an optical system for projecting an image of an object onto a display image plane of an optical panel at an incident angle which is greater than zero. The optical system comprises an image source and an imaging element. The
15 imaging element creates an image of the object in an intermediate image plane. The optical system also comprises an anamorphic element for reducing anamorphic distortion of the image and a telecentric element for reducing keystone-type distortion of the image. The present invention is also directed to a display system which includes the combination of an optical system and an optical panel.

20 The present invention solves problems experienced in the prior art, such as the use of expensive and cumbersome projection equipment, by providing an optical system having a

reduced optical path that produces an accurate image on a highly tilted inlet face surface relative to the image path, and which does not suffer from improperly focused images and image distortions which yield false aspect ratios of the original object and inconsistent, linear point-to-point mapping of the object to the image. The present invention also retains the
5 advantages which correspond to a stacked waveguide panel, such as improved contrast and minimized depth.

Those and other advantages and benefits of the present invention will become apparent from the detailed description of the invention hereinbelow.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

For the present invention to be clearly understood and readily practiced, the present invention will be described in conjunction with the following figures, wherein:

FIG. 1 is an isometric view schematic illustrating an ultrathin optical panel;

5 FIG. 2 is a side view cross sectional schematic of an ultrathin optical panel;

FIG. 3 is a schematic illustrating a horizontal and vertical cross section of an ultrathin optical panel using a prismatic coupler;

FIG. 4 is a simplified rear view schematic illustrating an optical system in conjunction with an optical panel; and

10 FIG. 5 is a side view cross sectional schematic of an ultrathin optical panel using a preferred optical system including a telecentric lens element.

FIG. 6 is a side view cross sectional schematic of an ultrathin optical panel using another preferred optical system including a telecentric mirror element.

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DETAILED DESCRIPTION OF THE INVENTION

It is to be understood that the figures and descriptions of the present invention have been simplified to illustrate elements that are relevant for a clear understanding of the present invention, while eliminating, for purposes of clarity, many other elements found in a typical optical display panel. Those of ordinary skill in the art will recognize that other elements are
20 desirable and/or required in order to implement the present invention. However, because

such elements are well known in the art, and because they do not facilitate a better understanding of the present invention, a discussion of such elements is not provided herein.

FIG. 1 is an isometric view schematic illustrating an optical panel 10. The optical panel 10 includes a plurality of waveguides 10a, wherein one end of each waveguide 10a forms an inlet for that waveguide, and wherein the opposite end of each waveguide 10a forms an outlet for that waveguide 10a, a light generation system 12, a housing 14 in which the light generation system 12 and the plurality of waveguides 10a are mounted, and a coupler 16.

Each waveguide 10a extends horizontally, and the plurality of stacked waveguides 10a extends vertically. The plurality of inlet ends define an inlet face 20 for receiving image light 22. The plurality of outlet ends define an outlet face 24 disposed substantially parallel with the inlet face 20 for displaying light 22. The light 22 may be displayed in a form such as, but not limited to, a video image 22a.

The housing 14 is sized larger in height and width than the combination of the light generation system 12 and the plurality of waveguides 10a, to allow the placement of the plurality 10a and light generation system 12 therein. The housing 14 has an open front to allow for viewing of the outlet face 24, and has a closed depth D looking from the open front to the back of the housing 14.

The light generation system 12 provides the light viewed through the waveguides 10a. The light generation system 12 includes a light source 30, and a light redirection element 32 that redirects incident light 22 from the light source 30 into the coupler 16, which light redirection element 32, in combination with the coupler 16, allows for a reduction in the

depth D of the housing 14. This reduction allowance occurs where the light redirection element 32 is configured for turning the light 22 from a source 30, which source 30 is placed within the housing 14 proximate to and parallel with the vertical stack of the plurality of waveguides 10a, into the coupler 16, which then acutely turns the light 22 into the

5 waveguides 10a. The coupler 16 is preferably effective for turning the image light in an exemplary range of about 45° up to about 90° , in order to generate approximately horizontal transmission through the plurality of waveguides 10a. The light generation system 12 may also include a modulator and further imaging optics. This light generation system 12 is discussed with more particularity with respect to FIG. 2.

10 The parallel surfaces of the inlet face 20 and the outlet face 24 allow the panel 10 and enclosing housing 14 to be made ultrathin in depth. The panel 10 has a nominal thickness T which is the depth of the waveguides 10a between the inlet face 20 and the outlet face 24, and thickness T is substantially less than the height H and width W of the outlet face 24. The panel 10 may be configured in typical television width to height ratios of 4:3 or 16:9, for

15 example. For a height H of about 100 cm and a width W of about 133 cm, the panel thickness T of the present invention may be about 1 cm. The depth D may vary accordingly with the thickness T, but, in the embodiment described hereinabove, the depth D of the housing 14 is preferably no greater than about 12 cm.

FIG. 2 is a side view cross sectional schematic of an ultrathin optical panel 10. The

20 panel 10 includes a plurality of stacked waveguides 10a, a light generation system 12, a coupler 16, and a housing 14.

The light generation system 12, in one embodiment of the present invention, includes a projector 60 which is optically aligned with a light redirection element 32. An image is projected onto the light redirection element 32, and is then redirected to the coupler 16 for transmission through the waveguides 10a for display on the outlet face 24. In a preferred
5 embodiment, the projector 60 is disposed adjacent to the top of the inlet face 20 for projecting the image light 22 generally parallel thereto, and is spaced therefrom a distance sufficient to allow for a turning of the image light 22 from the light redirection element 32 into the coupler 16 for transmission through the waveguides 10a.

The projector 60 may include a suitable light source 30 for producing the light 22.

10 The light source 30 may be a light bulb (e.g. filament or arc type) or laser. The projector 60 may be a slide projector or video projector which may include a modulator 62 for modulating the light 22 to form an image 22a. The modulator 62 may be, for example, a conventional Liquid Crystal Display (LCD), a Digital Micromirror Device (DMD), a GLV, a laser raster scanner, a PDLC, an LCOS, a MEMS, or a CRT. The projector 60 may also include suitable
15 image optics 64 for distributing or broadcasting the image light 22 horizontally and vertically across the light redirection element 32 for properly focused transmission to the coupler 16. The image optics 64 may include focusing and expanding lenses and/or mirrors. One or more light generation systems 12, such as between 2 and 4 such systems, may be used to provide light to one or more portions of the coupler 16. Expansion lenses may be used for both the
20 imaging optics 64 and the light redirection element 32 to expand the image light 22 both vertically and horizontally over the coupler 16. Alternatively, suitable rastering systems may

be used as the light generation system 12 to form the image by rastering the image light 22 both horizontally and vertically across the coupler 16.

In the illustrated embodiment, the light 22 is initially projected from the projector 60 vertically downward inside the housing 14 to the bottom thereof where the light redirection elements 32 are mounted, and the light redirection elements 32 then redirect the image light 22 vertically upwardly at a small acute angle for broadcast over the entire exposed surface of the coupler 16. In an alternative embodiment, the projector 60 could be placed beneath the inlet face 20 rather than behind the inlet face 20.

The allowable incidence angle of the image light 22 on the coupler 16 is determined by the capability of the coupler 16 to turn the light 22 into the inlet face 20 of the panel 10. The greater the turning capability of the coupler 16, the closer the projector 60 may be mounted to the coupler 16 for reducing the required depth D of the housing 14.

FIG. 3 is a schematic illustrating a horizontal and vertical cross section of an ultrathin optical panel 10. The panel 10 includes a plurality of vertically stacked optical waveguides 10a, a light generation system 12 (see FIG. 2), a coupler 16, and a housing 14.

Each waveguide 10a of the plurality of waveguides 10a includes a central transparent core 80 having a first index of refraction. The core 80 may be formed of any material known in the art to be suitable for passing light waves therethrough, such as, but not limited to plexiglass or polymers. The central core 80 may be formed of an optical plastic, such as Lexan®, commercially available from the General Electric Company®, or glass, such as type BK7. The preferred embodiment of the present invention is implemented using individual

glass sheets, which are typically in the range between 2 and 100 microns thick, and which may be of a manageable length and width. The central core 80 is laminated between at least two cladding layers 82. The cladding layers 82 immediately in contact with the glass have a second index of refraction lower than that of the cores 80, thus allowing for substantially total internal reflection of the light 22 as it is transmitted through the cores 80. The cladding 82 may be a suitable plastic, plexiglass, glass, adhesive, polyurethane, low refractive index polymer, or epoxy, for example, and is preferably black in color. Where multiple cladding layers 82 are used, it is preferable that a clear cladding layer contact the glass, and a black pigmented layer be disposed between adjacent clear cladding layers, thus improving both viewing contrast of the outlet face 24 and internal reflection of the light 22 through the core 80. The use of at least one black pigmented layer provides improved contrast by providing additional blackness at the outlet face 24. Further, the exposed edges of the black pigmented layer at the outlet face 24 are directly viewable by the observer. Additionally, ambient light which enters the waveguides off-axis through the outlet face 24 will be absorbed internally by the black pigmented layer. The black pigmented layer may be formed in any suitable manner such as with black spray paint, or carbon particles within an epoxy adhesive joining together the adjacent cores 80 in one or more black pigmented layers. The manner of forming the cladding layers 82 and cores 80 is discussed with more specificity hereinbelow.

The waveguides 10a of the preferred embodiment are in the form of flat ribbons extending continuously in the horizontal direction along the width of the outlet face 24. The ribbon waveguides 10a are preferably stacked vertically along the height of the outlet face 24.

The vertical resolution of the panel 10 is thus dependent on the number of waveguides 10a stacked along the height of the outlet face 24. For example, a stacking of 525 waveguides would provide 525 vertical lines of resolution.

The plurality of stacked waveguides 10a may be formed by first laying a first glass
5 sheet in a trough sized slightly larger than the first glass sheet. The trough may then be filled with a thermally curing epoxy. The epoxy is preferably black, in order to form a black layer between waveguides, thereby providing improved viewing contrast. Furthermore, the epoxy should possess the properties of a suitable cladding layer 82, such as having a lower index of refraction than the glass sheets to allow substantially total internal reflection of the light 22
10 within the glass sheet. After filling of the trough, glass sheets 80 are repeatedly stacked, and a layer of epoxy forms between each glass sheet 80. The stacking is preferably repeated until between approximately 500 and 800 sheets have been stacked. Uniform pressure may then be applied to the stack, thereby causing the epoxy to flow to a generally uniform level between glass sheets 80. In a preferred embodiment of the present invention, the uniform
15 level obtained is approximately .0002" between glass sheets 80. The stack may then be baked to cure at 80 degrees Celsius for such time as is necessary to cure the epoxy, and the stack is then allowed to cool slowly in order to prevent cracking of the glass. After curing, the stack may be placed against a saw, such as, but not limited to, a diamond saw, and cut to a desired size. The cut portions of the panel 10 may then be polished with a diamond polisher to
20 remove any saw marks.

In an alternative embodiment of the present invention, a plurality of glass sheets 80 are individually coated with, or dipped within, a substance having an index of refraction lower than that of the glass, and the plurality of coated sheets are fastened together using glue or thermally curing epoxy, which is preferably black in color. A first coated glass sheet 10a is placed in a trough sized slightly larger than the first coated glass sheet 10a, the trough is filled with a thermally curing black epoxy, and the coated glass sheets 10a are repeatedly stacked, forming a layer of epoxy between each coated glass sheet 10a. The stacking is preferably repeated until between approximately 500 and 800 sheets have been stacked. Uniform pressure may then be applied to the stack, followed by a cure of the epoxy, and a sawing of the stack into a desired size. The stack may be sawed curved or flat, and may be frosted or polished after sawing.

In another alternative embodiment of the present invention, the glass sheets 80 preferably have a width in the range between 0.5" and 1.0", and are of a manageable length, such as between 12" and 36". The sheets 80 are stacked, with a layer of black ultraviolet adhesive being placed between each sheet 80. Ultraviolet radiation is then used to cure each adhesive layer, and the stack may then be cut and/or polished.

After sawing and/or polishing the stack, each of the above embodiments of the method also includes bonding a coupler 16 to the inlet face 20 of the stack, and fastening the stack, having the coupler 16 bonded thereto, within the rectangular housing 14. The stack is fastened such that the open front of the housing 14 is aligned with the outlet face 24, and the light generator 12 within the housing 14 is optically aligned with the coupler 16.

The light generation system 12 provides light 22 which is incident on the coupler 16, and is substantially as discussed with respect to FIG. 2. The light source 30 of the light generation system 12 may be mounted within the housing 14 in a suitable location to minimize the volume and depth of the housing 14. The source 30 is preferably mounted within the housing 14 directly behind the inlet face 20 at the top thereof to initially project light 22 vertically downwardly, which light 22 is then turned by light redirection elements 32 of the light generation system 12 vertically upwardly to optically engage the coupler 16. In a preferred embodiment of the present invention, the individual waveguides 10a extend horizontally without inclination, thus allowing the image to be transmitted directly horizontally through the waveguides 10a for direct viewing by an observer, thereby allowing the viewer to receive full intensity of the light 22 for maximum brightness. A sheet of diffusing material may optionally be provided on the outlet face 24 to effect an improved viewing angle of the display. Alternatively, instead of a sheet of diffusing material, a diffusing surface may be formed into the outlet face 24 itself to effect a similarly improved viewing angle. Thus, for maximum brightness, the light 22 incident from the light generation system 12 must be turned substantially horizontally. A prismatic coupler 16 may be used to turn the light at an angle up to 90 degrees for entry into the inlet face 20. In one embodiment of the present invention, a Transmissive Right Angle Film (TRAF) turns the light at an angle of 81 degrees.

The light coupler 16 adjoins the entire inlet face 20 and may be suitably bonded thereto for coupling or redirecting the light 22 incident from the light generation system 12

into the inlet face 20 for transmission through the waveguides 10a. The waveguides 10a of the present invention may have a limited acceptance angle for receiving incident light 22, and the coupler 16 is aligned to ensure that the image light 22 is suitably turned to enter the waveguide cores 80 within the allowable acceptance angle.

5 In a preferred embodiment of the present invention, the coupler 16 includes Fresnel prismatic grooves 16a that are straight along the width of the inlet face 20 and are spaced vertically apart along the height of the inlet face 20, which prismatic coupler 16 is capable of turning light up to an angle of 90 degrees. In another preferred embodiment of the present invention, the prismatic coupler 16 is a TRAF commercially available from the 3M
10 Company® of St. Paul, Minneapolis, under the tradename TRAF II®. An optional reflector may be disposed closely adjacent to the prismatic coupler 16 for reflecting back into the waveguides 10a any stray light 22 at the grooves 16a. As still another preferred embodiment of the present invention, the coupler 16 (or light redirecting surface) may instead be formed into the inlet face 20 itself.

15 The coupler 16 may also take the form of a diffractive element 16. The diffractive coupler 16 includes a diffractive grating having a large number of small grooves extending horizontally and parallel with the individual waveguides 10a, which grooves are closely spaced together in the vertical direction over the height of the inlet face 20. The coupler 16 may take other forms as well, including, but not limited to, holographic elements.

20 The housing 14 supports the waveguide stack 10a and the light generation system 12 in a substantially closed enclosure. The outlet face 24 faces outwardly and is exposed to the

viewer and ambient light, and the inlet face 20 and adjoining coupler 16 face inwardly toward preferably black surfaces within the housing 14, thereby providing additional black for contrast at the outlet face 24. This additional black is provided at the outlet face 24 due to the passive nature of the waveguides 10a and the coupler 16. When these passive devices are enclosed in a black area, the outlet face 24 will appear black when not illuminated by image light 22 incident on the inlet face 20.

FIG. 4 is a simplified rear view schematic illustrating an optical system 100 used to project an image from an image source 110 onto an optical panel 10 (also shown for illustration purposes in FIG. 4). The optical system 100 may replace the light generation system 12 as described above in conjunction with FIG. 2. The optical system 100 includes an image source 110, an imaging element 120, an anamorphic element 130, and a telecentric element 140. The optical panel 10 may be of the type described in the embodiments above with respect to Figures 1-3. Alternatively, the optical panel may be of different type dependent on design choice or routine experimentation by the skilled artisan. The image source 110, imaging element 120, anamorphic element 130, and telecentric element 140 are all nominally symmetric about a single plane that ideally contains all of the centers of curvature of the optical elements. For purposes of this discussion only, this plane will be referred to herein as the "y-z plane".

As used herein, the incident angle θ is defined as the angle formed between a line drawn from the center of the object plane to the center of the display image plane, and a line perpendicular to the display image plane. This is illustrated in FIG. 5 in which the projection

system uses lenses, not mirrors. In embodiments where mirrors are used as optical elements in the projection system, the line from the center of the object plane to the center of the display image plane is "folded" or "reflected", as shown in FIG. 6, where the telecentric element is a mirror. The image is projected onto the display image plane at an incident angle θ greater than zero. In a preferred embodiment of the invention, incident angle θ is in the range of approximately 50° - 85° . In a more preferred embodiment of the invention, incident angle θ is approximately 78° .

Since the tilt associated with this configuration is substantial, optical tilting of the image plane is preferably spread out gradually over the entire optical train. In other words, the optical elements in the optical train, i.e. the imaging element 120, the anamorphic element 130, and the telecentric element 140, each effect a tilt on the image of the object. Although it is possible to accomplish this using only one or some of the optical elements in the optical train. The image source 110 and the imaging element 120 are each tilted about the x-axis. Tilting both the image source 110 and the imaging element 120 in this way makes use of the Scheimflug rule to effect an intermediate tilt on the image-plane.

The imaging element 120 creates an image of the object in an intermediate image plane at an angle intermediate to the angle between the plane of the image source 110 (the "object plane") and the targeted inlet face 20 plane (the "display image plane"). The anamorphic element 130 and telecentric element 140 are also tilted about the x-axis to effect a further intermediate tilt on the image-plane. Although the tilting by the anamorphic element

130 is not required for the optical system 100 to produce a tilted image, it is useful to provide some degree of tilt by the anamorphic element 130 to thereby improve image quality.

The image source 110 may be an illuminated object, e.g. an LCD or a DMD, or an emissive object, e.g. an LED array or a laser. The imaging element 120 preferably comprises
5 a rotationally symmetric surface and is comprised of glass or plastic, which may contain spherical or aspherical surfaces.

The anamorphic element 130 is provided in the optical system 100 mainly for reducing anamorphic distortion of the image and is preferably positioned subsequent the imaging element 120 within the optical path of the optical system 100. Although, in some
10 configurations, it may be desirable to position the imaging element 120 subsequent the anamorphic element 130 within the optical path of the optical system 100. For purposes of this disclosure, an anamorphic element is one which has a different optical power in each of two orthogonal axes (e.g. x and y).

The anamorphic element 130 preferably comprises three component groups, i.e. a
15 positive focusing group 131, a negative focusing group 132, and a negative image expanding group 133. Within each of these three component groups, there is at least one cylindrical or bi-laterally symmetrical element which has an aspherical surface. Each individual component group may optionally also include elements which have rotationally symmetric surfaces that are either spherical or aspherical. The individual component groups may each alternatively
20 be tilted or de-centered with respect to the central longitudinal optical axis 101 (FIG. 4) of the optical system 100 dependent on the amount or type of correction desired. These adjustments

to the individual component groups (i.e. tilting and de-centering) may be determined through routine experimentation and may therefore become apparent to the skilled artisan in light of the present disclosure. Each individual component group may be arranged or adjusted independently from the other remaining elements of the optical system 100 (including the remaining individual component groups within the anamorphic element 130). For example, the arrangement or adjustment may require the negative focusing group 132 to have a positive tilt with respect to the central longitudinal optical axis 101 of the optical system 100, while the positive focusing group 131 and negative image expanding group 133 each have a negative tilt with respect to the central longitudinal optical axis 101 of the optical system 100.

Other configurations will, of course, fall within the scope of the present invention in light of this description. Alternatively, exactly three component groups (within the anamorphic element 130) may not be required in all configurations. Although, ideally, each of the three component groups within the anamorphic element 130 effects a tilt on the image of the object, all that may be required is that the overall tilt effect be a certain value and this may be accomplished with fewer or greater component groups within the anamorphic element 130.

The exact number of component groups within the anamorphic element 130 may be dependent on the overall configuration of the optical system (including the above-mentioned tilting), the value for incident angle θ , and the image quality desired.

The telecentric element 140 in the optical system 100 is used mainly to reduce or eliminate the trapezoidal image distortion (otherwise known as "keystone-type" distortion) of the image that often occurs in an imaging system that has an incident angle θ greater than

zero. Also, if desired, the telecentric element 140 may optionally be used to introduce a tilt on the image of the object (as mentioned above) and may also optionally be used to focus the image. The telecentric element 140 is preferably positioned subsequent the anamorphic element 130 and imaging element 120 within the optical path of the optical system 100 and
5 may comprise either a lens, mirror, or a lens/mirror combination. As mentioned above, it may be desirable to provide the telecentric element 140 as a mirror as illustrated in FIG. 6 to effect a fold in the optical path of the optical system 100 to thereby reduce the overall depth D of the housing 14 (FIGs. 1-3) containing the optical panel 10 and optical system 100.

For purposes of this disclosure, a telecentric element is one which causes light rays to
10 become substantially parallel. In other words, light that reflects off a telecentric mirror element, or emerges from a telecentric lens element does not further separate (is not conical in shape) and thus, results in the object appearing to come from an infinite distance.

It may be desirable to tilt and de-center the telecentric element 140 with respect to the central longitudinal optical axis 101 of the optical system 100 dependent on the amount or
15 type of correction desired. These adjustments to the telecentric element 140 (i.e. tilting and de-centering) may be determined through routine experimentation and may therefore become apparent to the skilled artisan in light of the present disclosure. In the preferred embodiment, the telecentric element 140 may comprise a non-rotationally symmetric surface which is toroidal and/or aspherical in order to improve the quality of the image.

20 As an alternative to providing the telecentric element 140 as a lens, mirror, or lens/mirror combination as explained above, the reduction or elimination of the keystone-type

distortion may be performed electronically. For example, image source 110 may be a DMD configured to produce an image having an "inverse keystone-type distortion" which compensates for the keystone-type distortion caused by the optics of the projection path. Of course, this distortion correction technique can be used to compensate for any other distortion correction or focusing elements provided in the optical system. Although this technique has been described with reference to a DMD modulator, other modulators such as an LCD may be used.

FIG. 5 is a side view cross sectional schematic of an ultrathin optical panel 10 using a preferred optical system 100 of the type shown in FIG. 4. Commonly available optical design software such as, for example, ZEMAX (Focus Software, Inc.) may be used to assist in describing the various characteristics (e.g. radius, thickness, glass type, diameter, and whether the surface is conic) corresponding to each surface region of each individual elements/groups within the optical system 100. In the exemplary configuration shown in FIG. 4, the ZEMAX software outputs surface data describing these surface characteristics as illustrated in Table 1. The surface data for surfaces #4-#16 (illustrated in the left-hand column of Table 1) correspond to the imaging element 120. The surface data for surfaces #19-#26, #29-#31, and #35-#39 correspond to the positive focusing group 131, a negative focusing group 132, and a negative image expanding group 133, respectively, within the anamorphic element 130. The surface data for surface #43 correspond to the telecentric element 140.

Of course, other surface data values for each individual element/group will become apparent to those of ordinary skill in the art in light of the present disclosure and may

therefore be determined through routine experimentation dependent on the overall configuration and positioning of the individual elements/groups within the optical system 100 (including the above-mentioned tilting), the value for incident angle θ , and the quality of the image desired.

5

Table 1
ZEMAX Software Output Describing Surface Data Summary and Detail for Each Individual Element within the Optical System 100

10 SURFACE DATA SUMMARY:

	Surf	Type	Radius	Thickness	Glass	Diameter	Conic
	OBJ	STANDARD	Infinity	0		21.756	0
	1	STANDARD	Infinity	0		21.756	0
15	2	COORDBRK	-	292.175	-	-	-
	3	COORDBRK	-	-249.4148	-	-	-
	4	STANDARD	Infinity	10.69606	SFL6	64.80751	0
	5	STANDARD	-74.6184	19.99612		65.37593	0
	6	STANDARD	228.0807	10.34738	SK5	50.95582	0
20	7	STANDARD	-55.44567	4.999329	SF2	49.81779	0
	8	STANDARD	Infinity	19.96982		46.37759	0
	STO	STANDARD	Infinity	6		35.65802	0
	10	STANDARD	-45.74455	15.99918	SF2	37.60689	0
	11	STANDARD	Infinity	3.357388		56.80725	0
25	12	STANDARD	-184.6081	14.13996	LAKN22	58.86762	0
	13	STANDARD	-42.9287	8.995559	SF1	62.42738	0
	14	STANDARD	-66.38955	0.5		75.3492	0
	15	STANDARD	Infinity	15	SK5	88.60007	0
	16	STANDARD	-100.051	119.414		91.11639	0
30	17	COORDBRK	-	-84.414	-	-	-
	18	COORDBRK	-	0	-	-	-
	19	BICONICX	Infinity	20	BK7	157.8103	0
	20	IRREGULA	Infinity	-20		152.2011	0
	21	COORDBRK	-	108.4461	-	-	-
35	22	COORDBRK	-	0	-	-	-
	23	IRREGULA	Infinity	20	BK7	163.0092	0
	24	BICONICX	Infinity	0	SAN	214.3203	0
	25	BICONICX	Infinity	15	SFL56	214.3203	0
	26	BICONICX	Infinity	-35		227.1676	0
40	27	COORDBRK	-	189.2805	-	-	-
	28	COORDBRK	-	0	-	-	-
	29	BICONICX	Infinity	20	BK7	181.0634	0
	30	BICONICX	Infinity	0	SAN	201.5716	0
	31	BICONICX	Infinity	25	SFL56	201.5716	0
45	32	BICONICX	Infinity	-45		209.3956	0
	33	COORDBRK	-	364.5128	-	-	-
	34	COORDBRK	-	0	-	-	-

	35	IRREGULA	-194.006	35	POLYCARB	288.6875	0
	36	IRREGULA	-194.006	-35		309.3933	0
	37	COORDBRK	-	80	-	-	-
	38	COORDBRK	-	0	-	-	-
5	39	BICONICX	Infinity	30	ACRYLIC	306.0721	0
	40	BICONICX	Infinity	-30		252.3439	0
	41	COORDBRK	-	850	-	-	-
	42	COORDBRK	-	0	-	-	-
	43	BICONICX	-3722.143	0	MIRROR	367.4967	0
10	44	COORDBRK	-	-35	-	-	-
	45	COORDBRK	-	-415	-	-	-
	46	COORDBRK	-	0	-	-	-
	47	STANDARD	Infinity	-12.5	BK7	0	0
15	IMA	STANDARD	Infinity			1272.227	0

SURFACE DATA DETAIL:

	Surface	OBJ	:	STANDARD
	Surface	1	:	STANDARD
20	Surface	2	:	COORDBRK
	Decenter	X	:	0
	Decenter	Y	:	0
	Tilt	About X	:	-14
	Tilt	About Y	:	0
25	Tilt	About Z	:	0
	Order	:	Decenter then tilt	
	Surface	3	:	COORDBRK
	Decenter	X	:	0
	Decenter	Y	:	0
30	Tilt	About X	:	-3.6145015
	Tilt	About Y	:	0
	Tilt	About Z	:	0
	Order	:	Decenter then tilt	
	Surface	4	:	STANDARD
35	Surface	5	:	STANDARD
	Surface	6	:	STANDARD
	Surface	7	:	STANDARD
	Surface	8	:	STANDARD
	Surface	STO	:	STANDARD
40	Surface	10	:	STANDARD
	Surface	11	:	STANDARD
	Surface	12	:	STANDARD
	Surface	13	:	STANDARD
	Surface	14	:	STANDARD
45	Surface	15	:	STANDARD
	Surface	16	:	STANDARD
	Surface	17	:	COORDBRK
	Decenter	X	:	0
	Decenter	Y	:	0
50	Tilt	About X	:	3.6145015
	Tilt	About Y	:	0
	Tilt	About Z	:	0
	Order	:	Decenter then tilt	
	Surface	18	:	COORDBRK
55	Decenter	X	:	0
	Decenter	Y	:	0
	Tilt	About X	:	-33.784948


```

Tilt About Y : 0
Tilt About Z : 0
Order : Tilt then decenter
Surface 19 : BICONICX
5 X Radius : 173.59718
X Conic : 0
Aperture : Rectangular Aperture
X Half Width : 50
Y Half Width : 57
10 Y- Decenter : -35
Surface 20 : IRREGULA
Decenter X : 0
Decenter Y : 0
Tilt X : 0
15 Tilt Y : 0
Spherical : 0
Astigmatism : 0
Coma : 0
Aperture : Rectangular Aperture
20 X Half Width : 50
Y Half Width : 57
Y- Decenter : -35
Surface 21 : COORDBRK
Decenter X : 0
25 Decenter Y : 0
Tilt About X : 33.784948
Tilt About Y : 0
Tilt About Z : 0
Order : Decenter then tilt
30 Surface 22 : COORDBRK
Decenter X : 0
Decenter Y : 0
Tilt About X : -37.672381
Tilt About Y : 0
35 Tilt About Z : 0
Order : Tilt then decenter
Surface 23 : IRREGULA
Decenter X : 0
Decenter Y : 0
40 Tilt X : 0
Tilt Y : 0
Spherical : 0
Astigmatism : 0
Coma : 0
45 Aperture : Rectangular Aperture
X Half Width : 35
Y Half Width : 70
Y- Decenter : -48
Surface 24 : BICONICX
50 X Radius : -218.64119
X Conic : 0
Aperture : Rectangular Aperture
X Half Width : 35
Y Half Width : 70
55 Y- Decenter : -48
Surface 25 : BICONICX
X Radius : -218.64119

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X Conic      : 0
Aperture     : Rectangular Aperture
X Half Width : 35
Y Half Width : 70
5 Y- Decenter : -48
Surface 26   : BICONICX
X Radius     : 173.59718
X Conic      : 0
Aperture     : Rectangular Aperture
10 X Half Width : 35
Y Half Width : 70
Y- Decenter  : -48
Surface 27   : COORDBRK
Decenter X   : 0
15 Decenter Y   : 0
Tilt About X : 37.672381
Tilt About Y : 0
Tilt About Z : 0
Order        : Decenter then tilt
20 Surface 28   : COORDBRK
Decenter X   : 0
Decenter Y   : 0
Tilt About X : -19.557286
Tilt About Y : 0
25 Tilt About Z : 0
Order        : Decenter then tilt
Surface 29   : BICONICX
X Radius     : -97.933517
X Conic      : 0
30 Aperture     : Rectangular Aperture
X Half Width : 58
Y Half Width : 65
Y- Decenter  : -43
Surface 30   : BICONICX
35 X Radius     : 218.64119
X Conic      : 0
Aperture     : Rectangular Aperture
X Half Width : 58
Y Half Width : 65
40 Y- Decenter : -43
Surface 31   : BICONICX
X Radius     : 218.64119
X Conic      : 0
Aperture     : Rectangular Aperture
45 X Half Width : 58
Y Half Width : 65
Y- Decenter  : -43
Surface 32   : BICONICX
X Radius     : -218.64119
50 X Conic      : 0
Aperture     : Rectangular Aperture
X Half Width : 58
Y Half Width : 65
Y- Decenter  : -43
55 Surface 33   : COORDBRK
Decenter X   : 0
Decenter Y   : 0

```

```

Tilt About X : 19.557286
Tilt About Y : 0
Tilt About Z : 0
Order : Decenter then tilt
5 Surface 34 : COORDBRK
  Decenter X : 0
  Decenter Y : -53.183452
  Tilt About X : -2.0483201
  Tilt About Y : 0
10 Tilt About Z : 0
  Order : Decenter then tilt
  Surface 35 : IRREGULA
  Decenter X : 0
  Decenter Y : 0
15 Tilt X : 0
  Tilt Y : 0
  Spherical : 0
  Astigmatism : 0
  Coma : 0
20 Aperture : Rectangular Aperture
  X Half Width : 90
  Y Half Width : 80
  Surface 36 : IRREGULA
  Decenter X : 0
25 Decenter Y : 0
  Tilt X : 4.132604
  Tilt Y : 0
  Spherical : 0
  Astigmatism : 0
30 Coma : 0
  Aperture : Rectangular Aperture
  X Half Width : 90
  Y Half Width : 80
  Surface 37 : COORDBRK
35 Decenter X : 0
  Decenter Y : 53.183452
  Tilt About X : 2.0483201
  Tilt About Y : 0
  Tilt About Z : 0
40 Order : Tilt then decenter
  Surface 38 : COORDBRK
  Decenter X : 0
  Decenter Y : 0
  Tilt About X : 11.853793
45 Tilt About Y : 0
  Tilt About Z : 0
  Order : Decenter then tilt
  Surface 39 : BICONICX
  X Radius : -108.26109
50 X Conic : -0.43754756
  Aperture : Rectangular Aperture
  X Half Width : 90
  Y Half Width : 78
  Y- Decenter : -63
55 Surface 40 : BICONICX
  X Radius : 0
  X Conic : 0

```

```

Aperture      : Rectangular Aperture
X Half Width  :      110
Y Half Width  :      78
Y- Decenter   :      -63
5  Surface 41  : COORDBRK
    Decenter X :      0
    Decenter Y :      0
    Tilt About X :    -11.853793
    Tilt About Y :      0
10  Tilt About Z :      0
    Order      : Decenter then tilt
Surface 42     : COORDBRK
    Decenter X :      0
    Decenter Y :      0
15  Tilt About X :      6.25
    Tilt About Y :      0
    Tilt About Z :      0
    Order      : Decenter then tilt
Surface 43     : BICONICX
20  X Radius    :    -2108.2232
    X Conic     :      0
    Aperture    : Rectangular Aperture
    X Half Width :      510
    Y Half Width :      92
25  Y- Decenter :     -92
Surface 44     : COORDBRK
    Decenter X :      0
    Decenter Y :      0
    Tilt About X :      0
30  Tilt About Y :      0
    Tilt About Z :      0
    Order      : Decenter then tilt
Surface 45     : COORDBRK
    Decenter X :      0
35  Decenter Y :      0
    Tilt About X :      6.25
    Tilt About Y :      0
    Tilt About Z :      0
    Order      : Decenter then tilt
40  Surface 46  : COORDBRK
    Decenter X :      0
    Decenter Y :    -78.542123
    Tilt About X :      79
    Tilt About Y :      0
45  Tilt About Z :      0
    Order      : Decenter then tilt
Surface 47     : STANDARD
    Aperture    : Rectangular Aperture
    X Half Width :      518
50  Y Half Width :      391
    Y- Decenter :      4
Surface IMA     : STANDARD
    Aperture    : Rectangular Aperture
    X Half Width :      518
55  Y Half Width :      391

```

The optical system 100 as described above produces a properly focused image on the surface of the inlet face 20 of an optical panel 10 and retains the aspect ratio of the original object while maintaining a linear point-to-point mapping of the object to the image.

5 Those of ordinary skill in the art will recognize that many modifications and variations of the present invention may be implemented. For example, instead of comprising lenses, the imaging element 120 and anamorphic element 130 each may alternatively comprise a mirror or lens/mirror combination. It may be desirable to provide the imaging
10 element 120 and/or anamorphic element 130 as a mirror or to provide additional mirror elements to effect a fold or multiple folds in the optical path of the optical system 100 to thereby reduce the overall depth D of the housing 14 (FIGs. 1-3) containing the optical panel 10 and optical system 100. The foregoing description and the following claims are intended to cover all such modifications and variations.

CLAIMS

What is claimed is:

1. An optical system for projecting an image of an object onto a display image plane at
5 an incident angle θ which is greater than zero, comprising:
an image source;
an imaging element for creating an image of the object in an intermediate image
plane;
an anamorphic element for reducing anamorphic distortion of the image; and
10 a telecentric element for reducing keystone-type distortion of the image.
2. The system of claim 1, wherein the intermediate image plane is at an angle
intermediate to the angle between an object plane and the display image plane.
- 15 3. The system of claim 1, wherein a center of curvature of the imaging element,
anamorphic element, and telecentric element are each aligned within a common plane.
4. The system of claim 1, wherein the imaging element is a mirror.
- 20 5. The system of claim 1, wherein the imaging element is a lens.
6. The system of claim 1, wherein the imaging element is a combination of a lens and a
mirror.

7. The system of claim 1, wherein the imaging element comprises a rotationally symmetric surface.

8. The system of claim 7, wherein the imaging element comprises an aspherical surface.

5

9. The system of claim 1, wherein the imaging element, the anamorphic element, and the telecentric element each effect a tilt on the image of the object.

10. The system of claim 1, wherein one or two elements selected from the group

10 consisting of the imaging element, the anamorphic element, and the telecentric element effect a tilt on the image of the object.

11. The system of claim 1, wherein the anamorphic element is a mirror.

15 12. The system of claim 1, wherein the anamorphic element is a lens.

13. The system of claim 1, wherein the anamorphic element is a combination of a lens and a mirror.

20 14. The system of claim 1, wherein the anamorphic element comprises a rotationally symmetric surface.

15. The system of claim 14, wherein the imaging element and telecentric element are each aligned along a central longitudinal optical axis, and wherein the anamorphic element is tilted
25 and de-centered with respect to the central longitudinal optical axis.

16. The system of claim 14, wherein the anamorphic element comprises spherical and aspherical surfaces.

5 17. The system of claim 14, wherein the imaging element and telecentric element are each aligned along a central longitudinal optical axis, and wherein the anamorphic element comprises spherical and aspherical surfaces and is tilted and de-centered with respect to the central longitudinal optical axis.

10 18. The system of claim 1, wherein the anamorphic element includes a positive focusing group, a negative focusing group, and a negative image expanding group.

19. The system of claim 18, wherein each group within the anamorphic element effects a tilt on the image of the object.

15

20. The system of claim 18, wherein each group within the anamorphic element includes at least one cylindrical element or bi-laterally symmetric aspherical element.

21. The system of claim 1, wherein the telecentric element is a mirror.

20

22. The system of claim 1, wherein the telecentric element is a lens.

23. The system of claim 1, wherein the telecentric element is a combination of a lens and a mirror.

25

24. The system of claim 1, wherein the telecentric element comprises an aspherical surface.

25. The system of claim 1, wherein the telecentric element comprises a toroidal surface.

5

26. The system of claim 1, wherein the telecentric element comprises a non-rotationally symmetric surface.

27. The system of claim 1, wherein the telecentric element comprises a non-rotationally symmetric surface which is aspherical.

10

28. The system of claim 1, wherein the telecentric element comprises a Fresnel surface.

29. The system of claim 1, wherein the display image plane is defined by end portions of a plurality of optical waveguides.

15

30. The system of claim 1, wherein the incident angle θ is in the range of approximately 50° - 85° .

31. The system of claim 30, wherein the incident angle θ is approximately 78° .

20

32. A display system having an optical panel and at least one optical system for projecting an image of an object onto a display image plane at an incident angle θ which is greater than zero, said display system comprising:

an optical panel, comprising:

25

a plurality of stacked optical waveguides, each having a first end and a second end, wherein an outlet face is defined by the plurality of first ends, and wherein an inlet face is defined by the plurality of second ends; and

at least one coupler provided at the inlet face which redirects light traveling
5 from an axis non-perpendicular to the inlet face to an axis perpendicular to the inlet face;

at least one optical system, each said optical system comprising:

an image source;

an imaging element for creating an image of the object in an intermediate
image plane;

10 an anamorphic element for reducing anamorphic distortion of the image; and

a telecentric element for reducing keystone-type distortion of the image.

33. The system of claim 32, wherein the intermediate image plane is at an angle
intermediate to the angle between an object plane and the display image plane.

15

34. The system of claim 32, wherein a center of curvature of the imaging element,
anamorphic element, and telecentric element are each aligned within a common plane.

35. The system of claim 32, wherein the imaging element is a mirror.

20

36. The system of claim 32, wherein the imaging element is a lens.

37. The system of claim 32, wherein the imaging element is a combination of a lens and a
mirror.

25

38. The system of claim 32, wherein the imaging element comprises a rotationally symmetric surface.

39. The system of claim 38, wherein the imaging element comprises an aspherical
5 surface.

40. The system of claim 32, wherein the imaging element, the anamorphic element, and the telecentric element each effect a tilt on the image of the object.

10 41. The system of claim 32, wherein one or two elements selected from the group consisting of the imaging element, the anamorphic element, and the telecentric element effect a tilt on the image of the object.

42. The system of claim 32, wherein the anamorphic element is a mirror.

15

43. The system of claim 32, wherein the anamorphic element is a lens.

44. The system of claim 32, wherein the anamorphic element is a combination of a lens and a mirror.

20

45. The system of claim 32, wherein the anamorphic element comprises a rotationally symmetric surface.

46. The system of claim 45, wherein the imaging element and telecentric element are each aligned along a central longitudinal optical axis, and wherein the anamorphic element is tilted and de-centered with respect to the central longitudinal optical axis.

5 47. The system of claim 45, wherein the anamorphic element comprises spherical and aspherical surfaces.

48. The system of claim 45, wherein the imaging element and telecentric element are each aligned along a central longitudinal optical axis, and wherein the anamorphic element
10 comprises spherical and aspherical surfaces and is tilted and de-centered with respect to the central longitudinal optical axis.

49. The system of claim 32, wherein the anamorphic element includes a positive focusing group, a negative focusing group, and a negative image expanding group.

15

50. The system of claim 49, wherein each group within the anamorphic element effects a tilt on the image of the object.

51. The system of claim 49, wherein each group within the anamorphic element includes
20 at least one cylindrical element or bi-laterally symmetric aspherical element.

52. The system of claim 32, wherein the telecentric element is a mirror.

53. The system of claim 32, wherein the telecentric element is a lens.

25

54. The system of claim 32, wherein the telecentric element is a combination of a lens and a mirror.

55. The system of claim 32, wherein the telecentric element comprises an aspherical
5 surface.

56. The system of claim 32, wherein the telecentric element comprises a toroidal surface.

57. The system of claim 32, wherein the telecentric element comprises a non-rotationally
10 symmetric surface.

58. The system of claim 32, wherein the telecentric element comprises a non-rotationally symmetric surface which is aspherical.

15 59. The system of claim 32, wherein the telecentric element comprises a Fresnel surface.

60. The system of claim 32, wherein the display image plane is defined by the plurality of second ends of the plurality of waveguides.

20 61. The system of claim 32, wherein the incident angle θ is in the range of approximately 50° - 85° .

62. The system of claim 61, wherein the incident angle θ is approximately 78° .

63. The system of claim 32, wherein the display system comprises two or more optical systems.

64. The system of claim 32, wherein the display system comprises three optical systems,
5 wherein the optical systems project red, green and blue light, respectively.

65. The system of claim 32, wherein each of the plurality of waveguides are formed as flat ribbons extending continuously in a horizontal direction along the outlet face.

10 66. A method for projecting an image of an object onto a display image plane at an incident angle θ which is greater than zero, said method comprising the steps of:
projecting an image from an image source;
directing the image of the object to an intermediate image plane with an imaging element;
15 reducing anormorphic distortion of the image with an anamorphic element; and
reducing keystone-type distortion of the image with a telecentric element.

67. A method for displaying an image of an object onto a display image plane of an optical panel at an incident angle θ which is greater than zero, said method comprising the
20 steps of:
projecting an image from an image source;
directing the image of the object to an intermediate image plane with an imaging element;
reducing anormorphic distortion of the image with an anamorphic element; and
25 reducing keystone-type distortion of the image with a telecentric element;

wherein the optical panel comprises a plurality of stacked optical waveguides, each having a first end and a second end, wherein an outlet face is defined by the plurality of first ends, wherein an inlet face is defined by the plurality of second ends, and wherein the optical panel further comprises at least one coupler at the inlet face to redirect light traveling from an
5 axis non-perpendicular to the inlet face to an axis perpendicular to the inlet face.

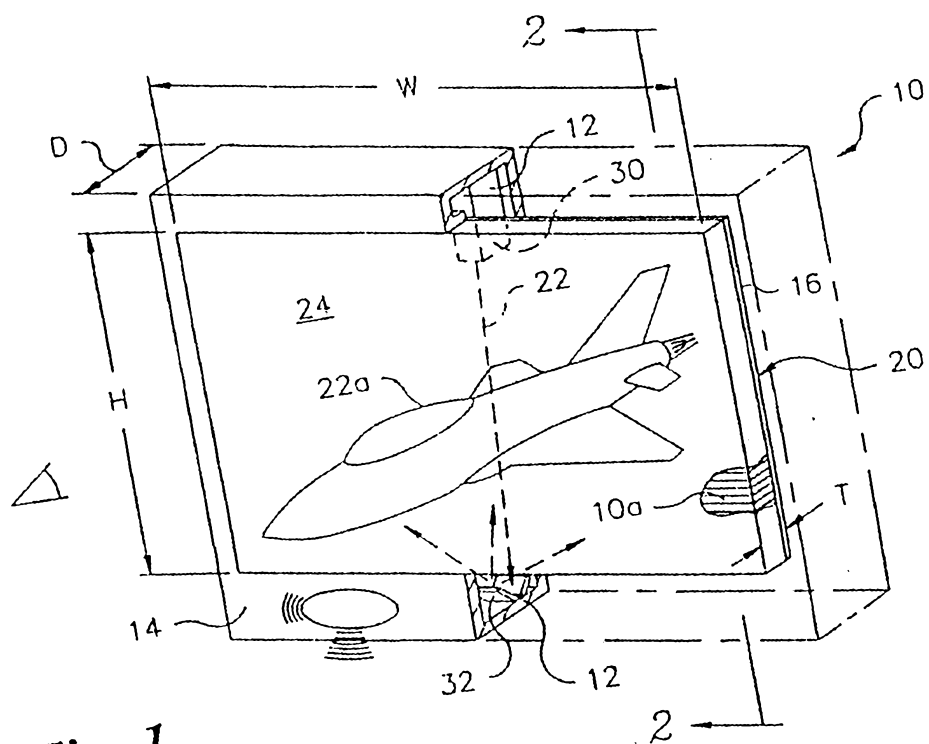
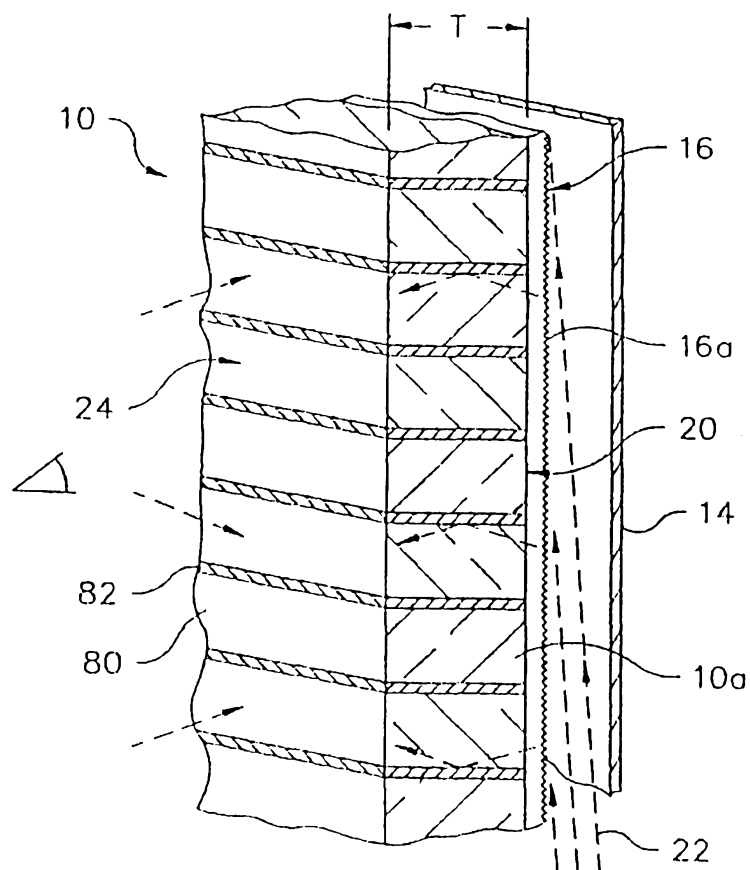
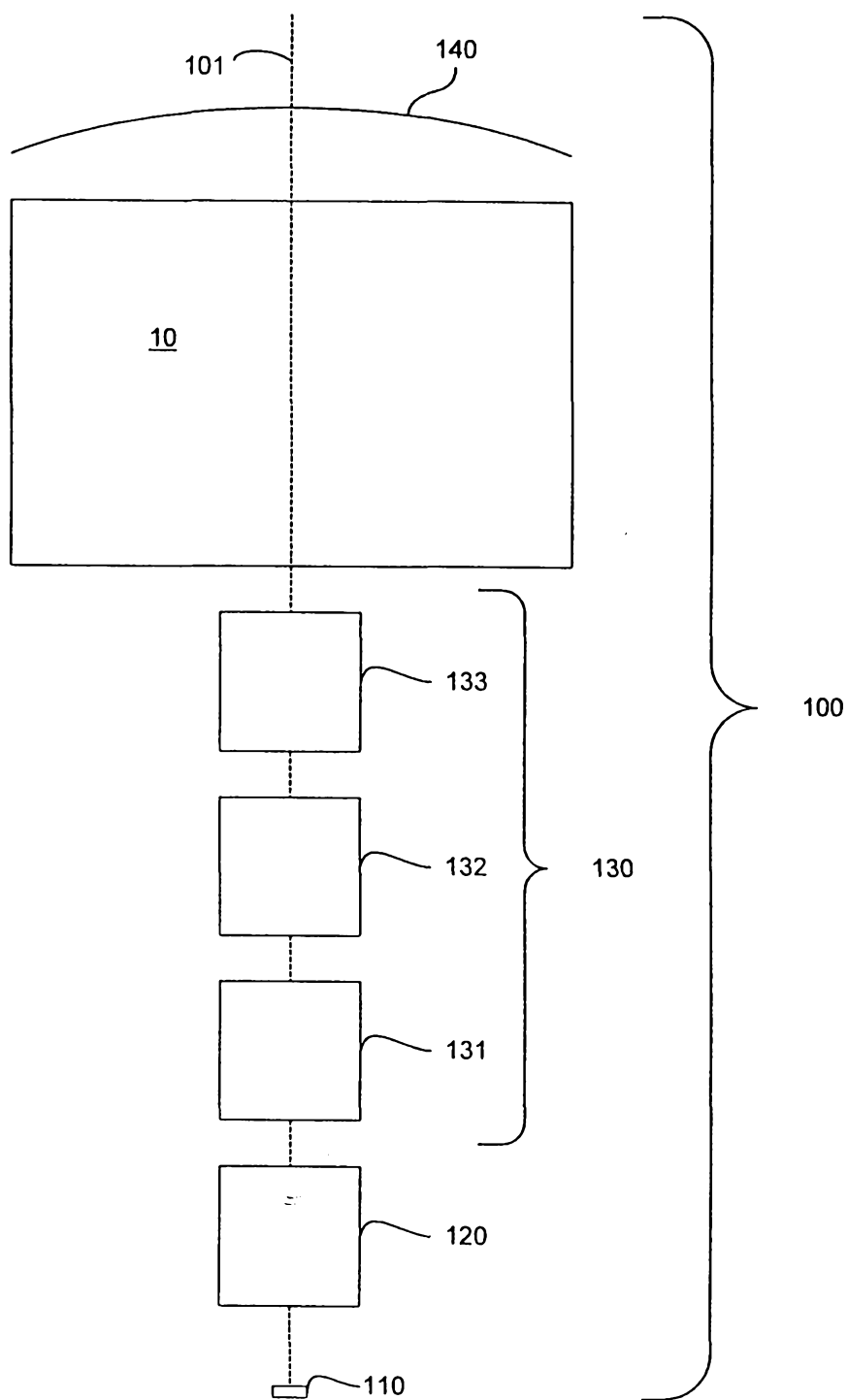


Fig. 1

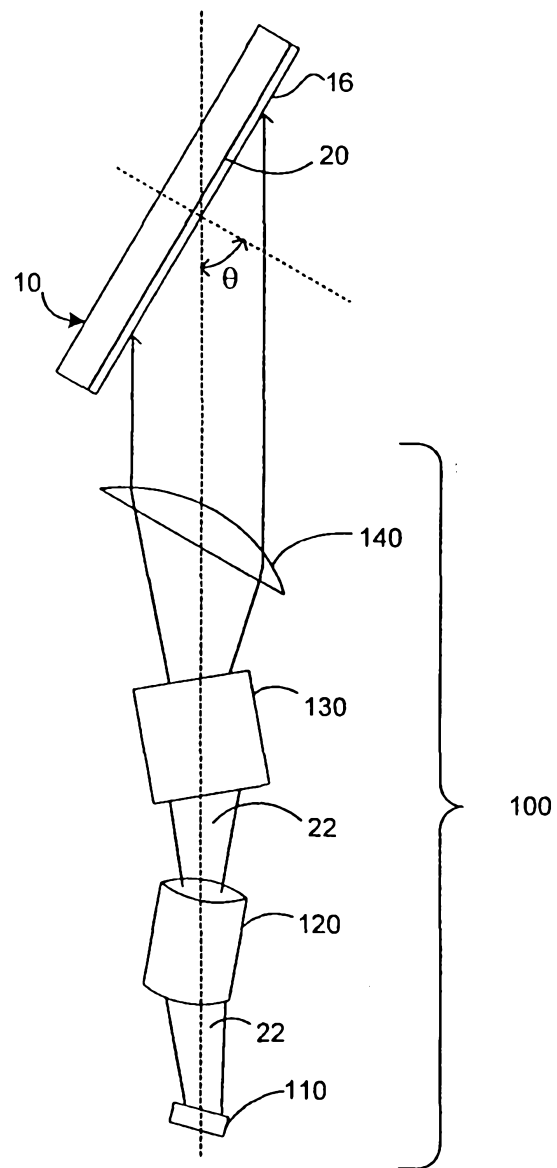
3/6

*Fig. 3*

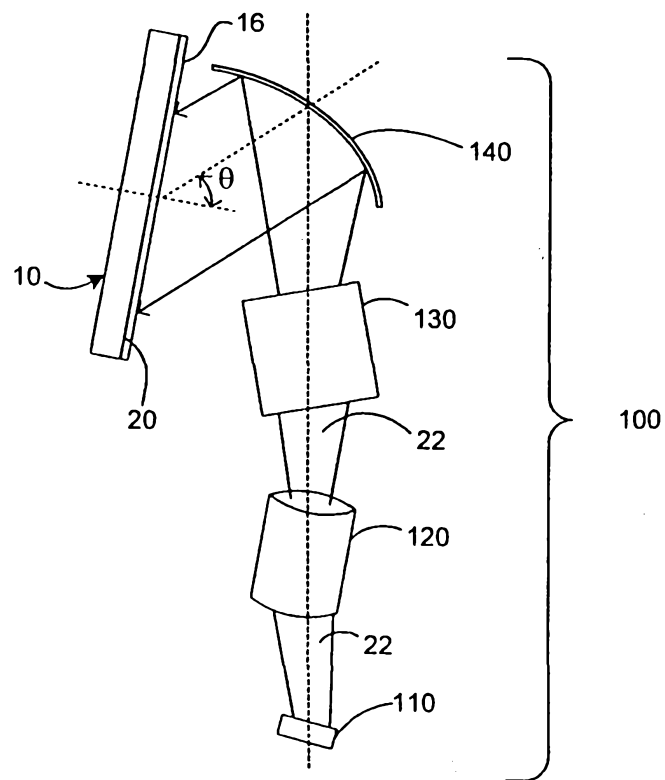
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***Fig. 4***

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***Fig. 5***

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***Fig. 6***