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Travis et al.

(54) **FLAT PANEL LENS**

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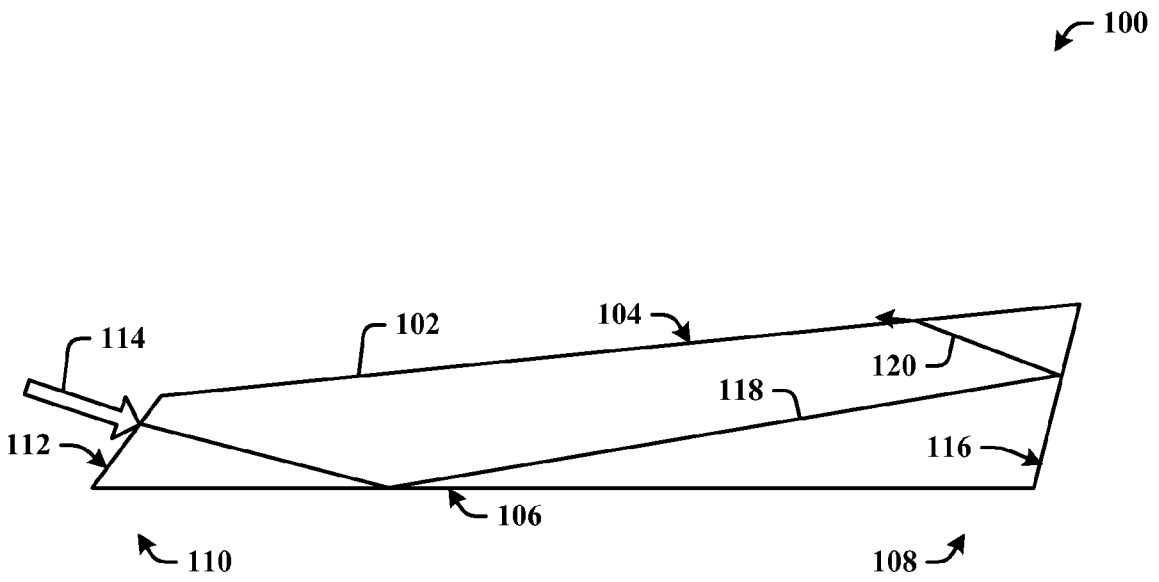
(57) **ABSTRACT**

A flat panel lens system as a tapered light guide that has minimal or no margin for fan out. The tapered light guide includes a thin end, and a thick end of which is a bevelled mirror or an optical equivalent. Light is injected into the thin end and the mirror is such that rays injected through a point at the thin end emerge collimated from one of the light guide surfaces, and that collimated rays injected at an appropriate angle through one of the light guide surfaces emerge from a point at the thin end. Bragg gratings can be utilized for color implementations as well. The tapered light guide can be fabricated as a single piece, by extrusion, injection molding, or the combination/variation of extrusion and injection molding, as well as other commonly known techniques.



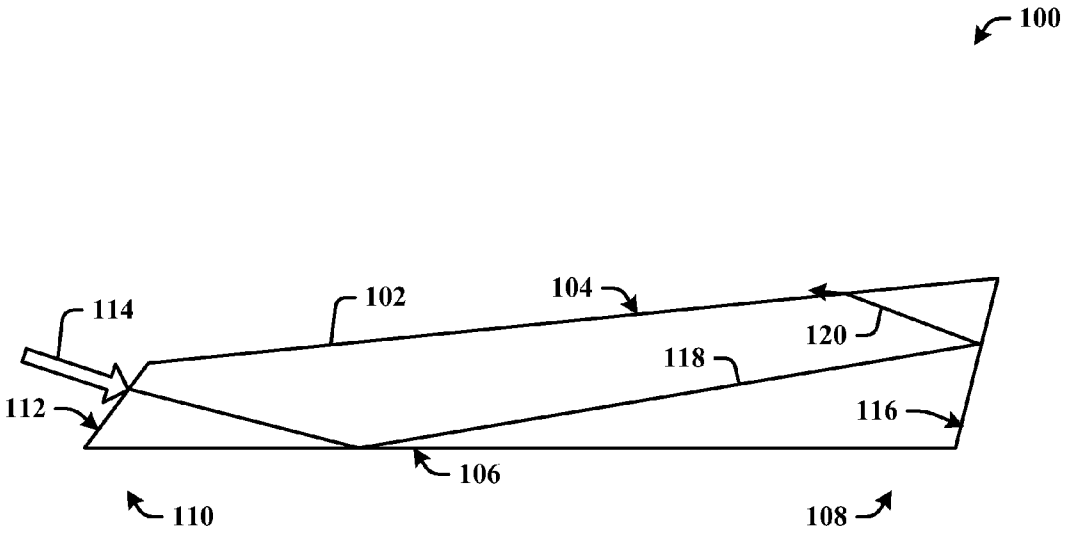
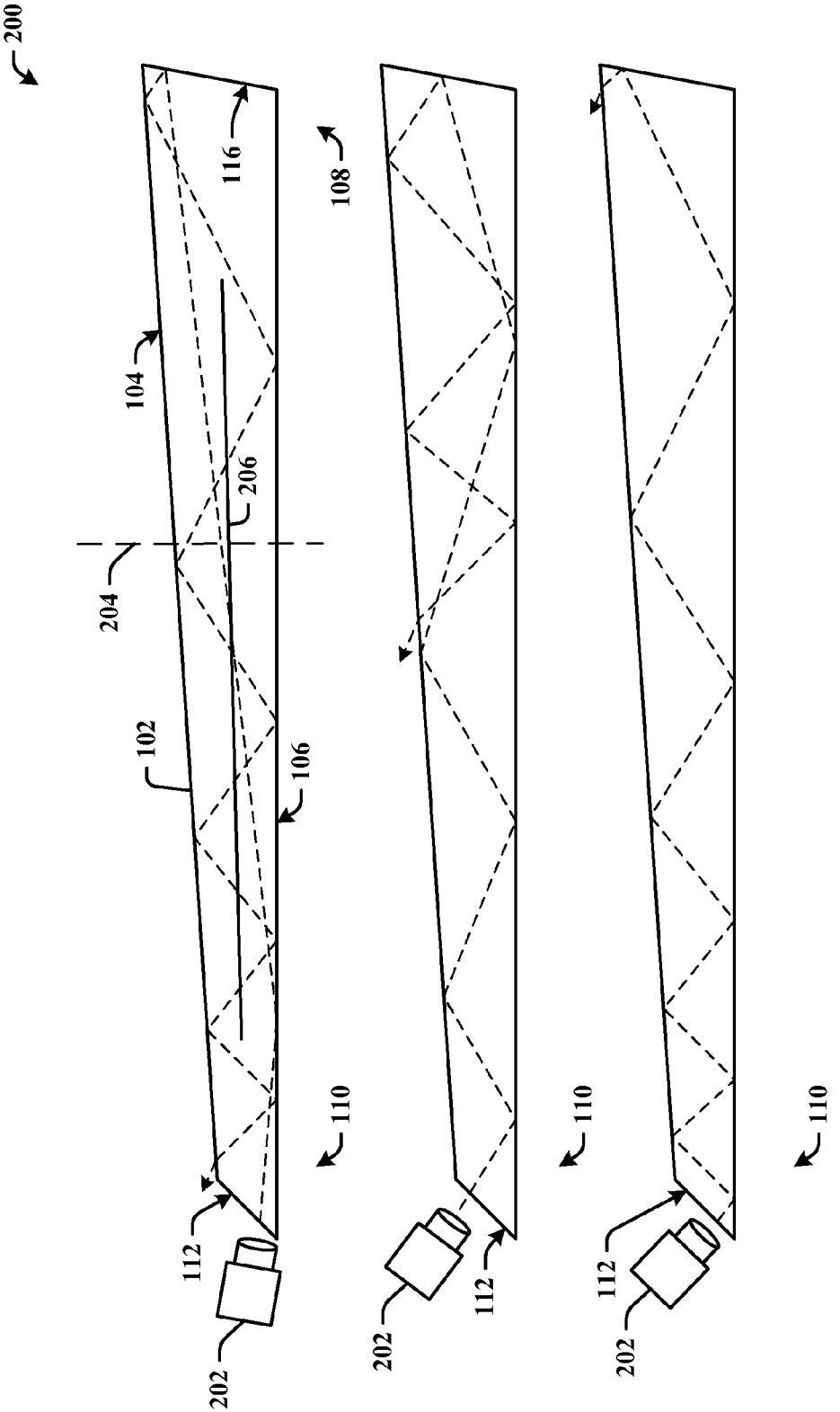


FIG. 1


200
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202

FIG. 2

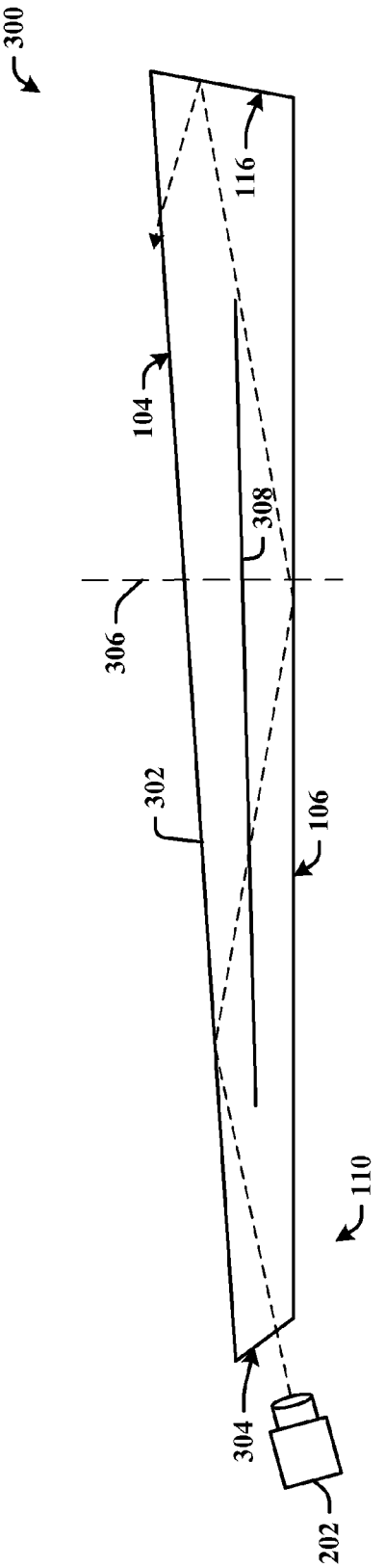

FIG. 3

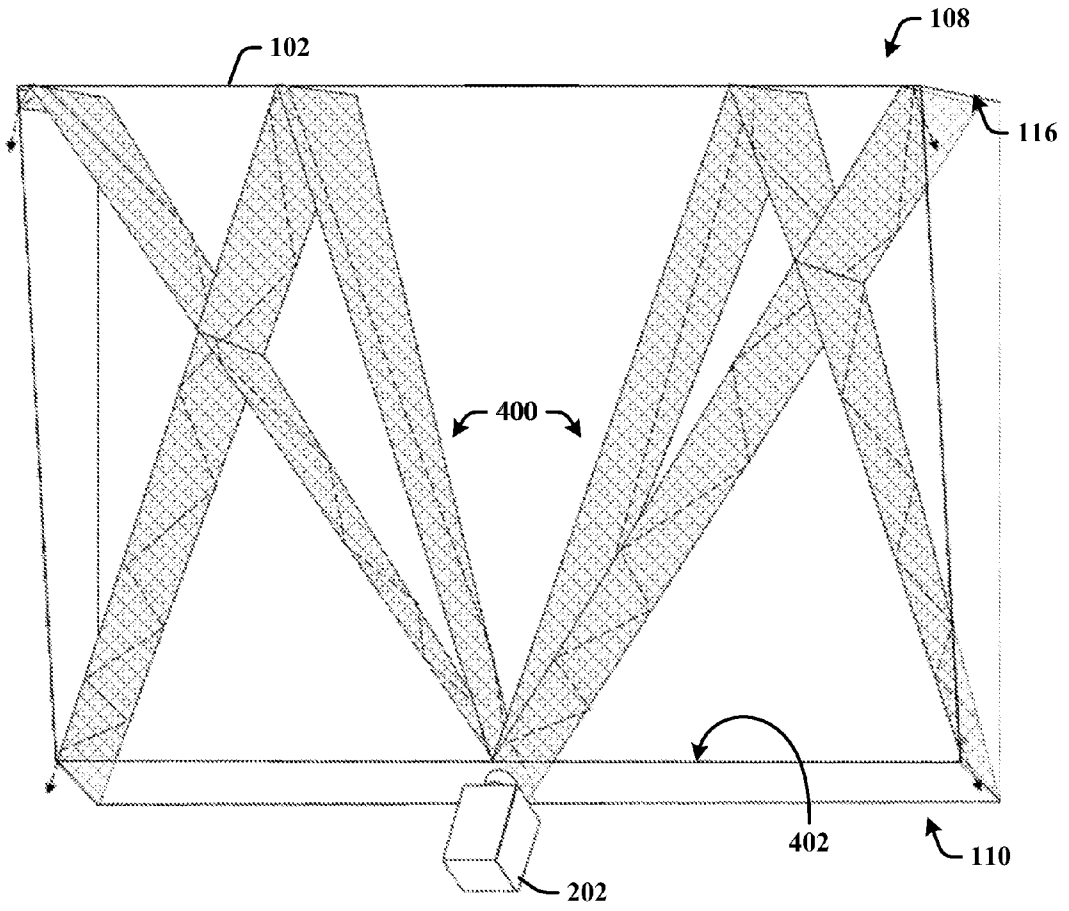

FIG. 4

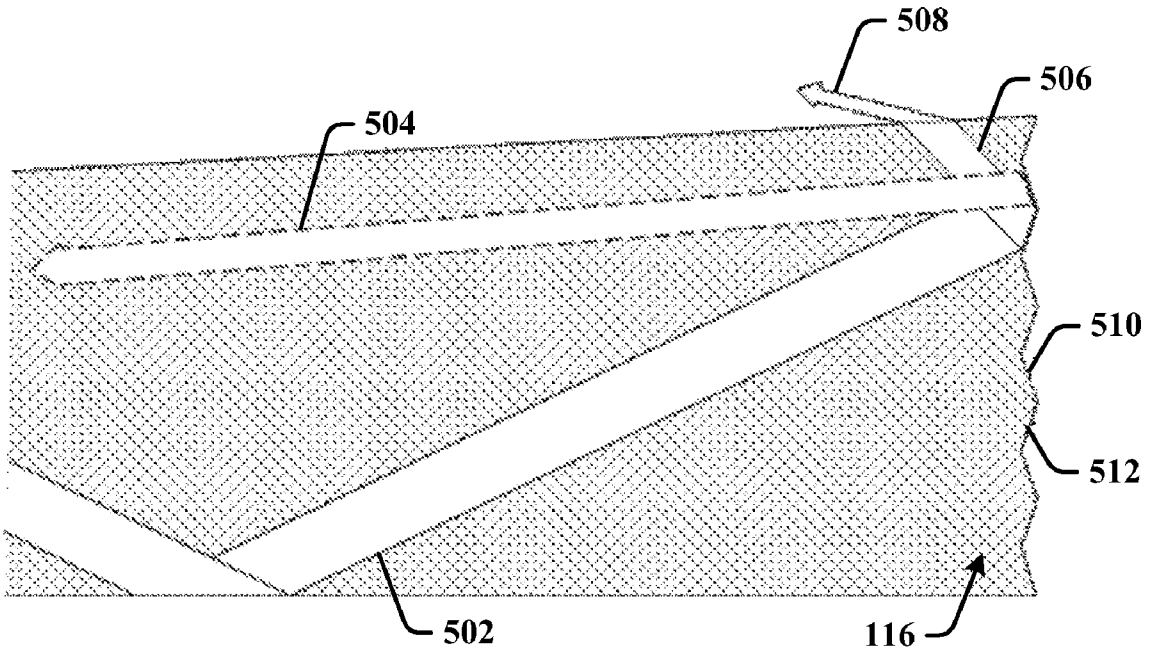

FIG. 5

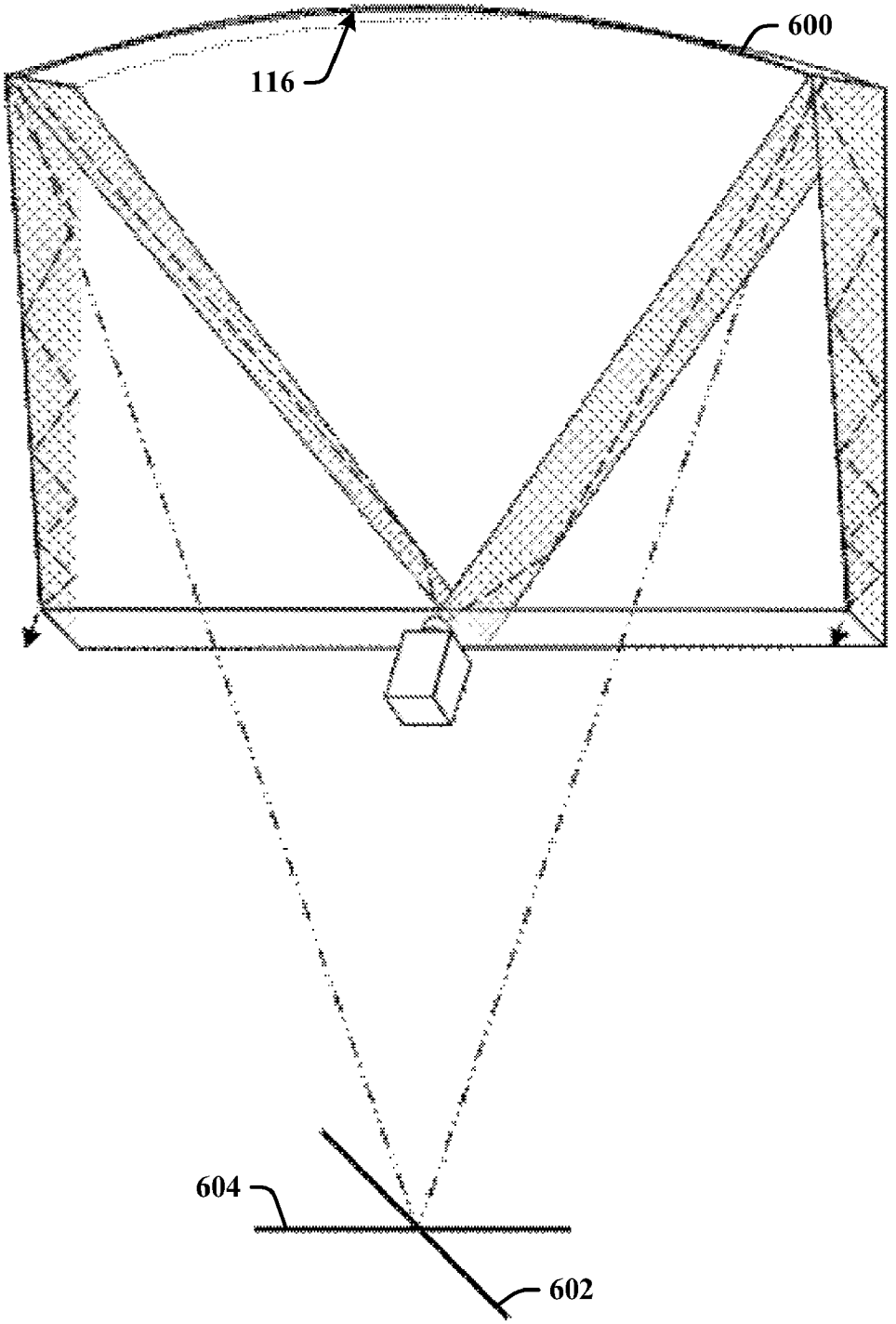

FIG. 6

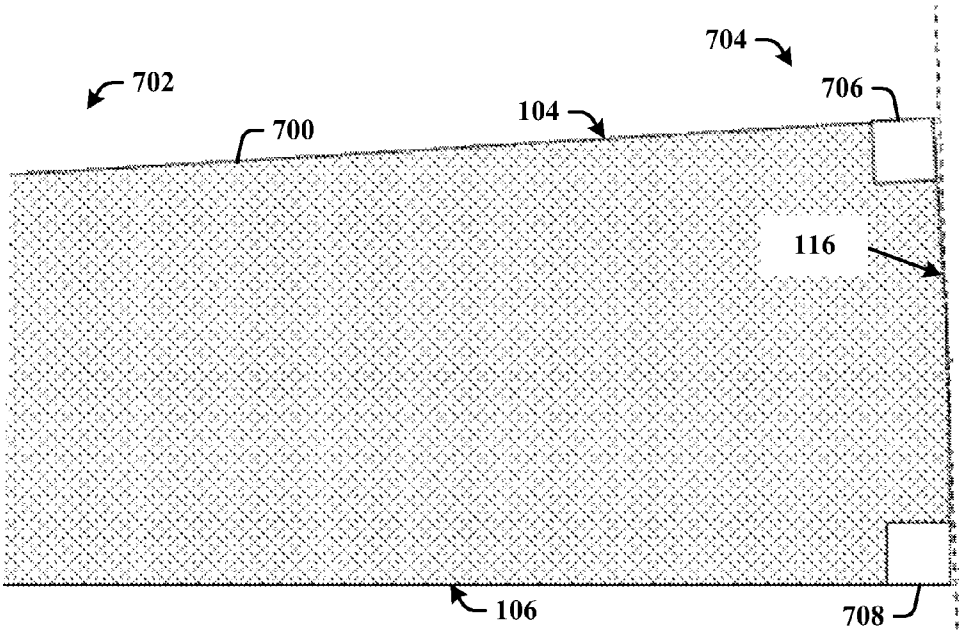

FIG. 7

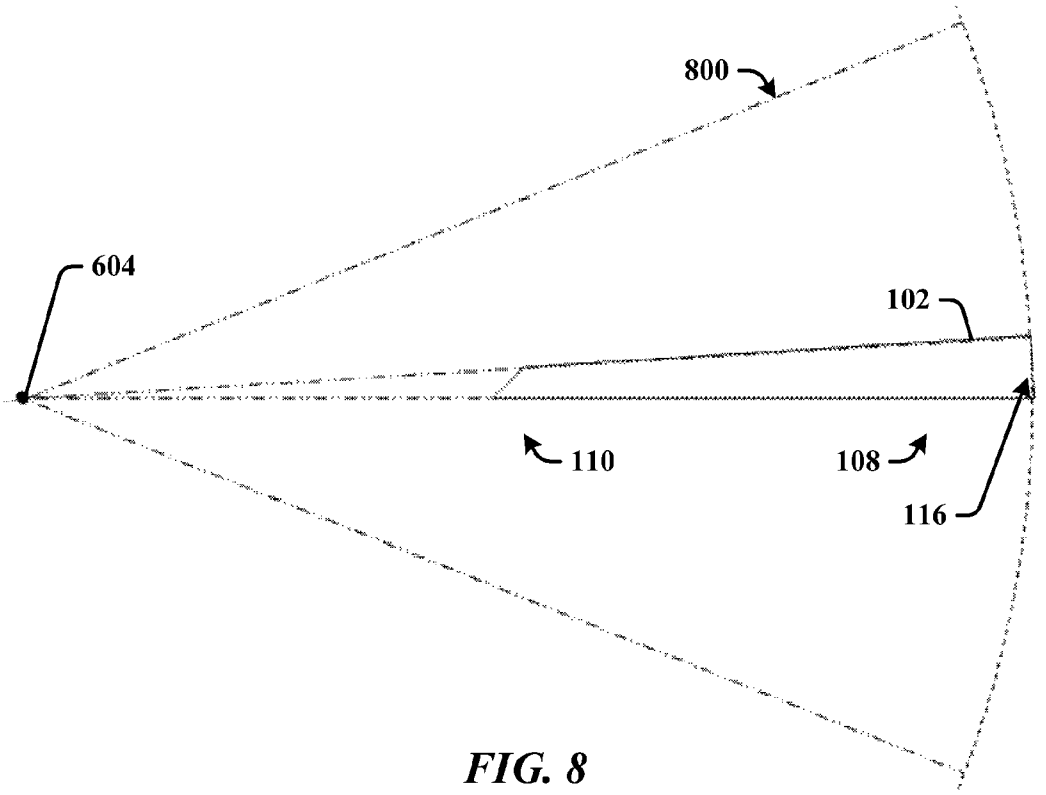

FIG. 8

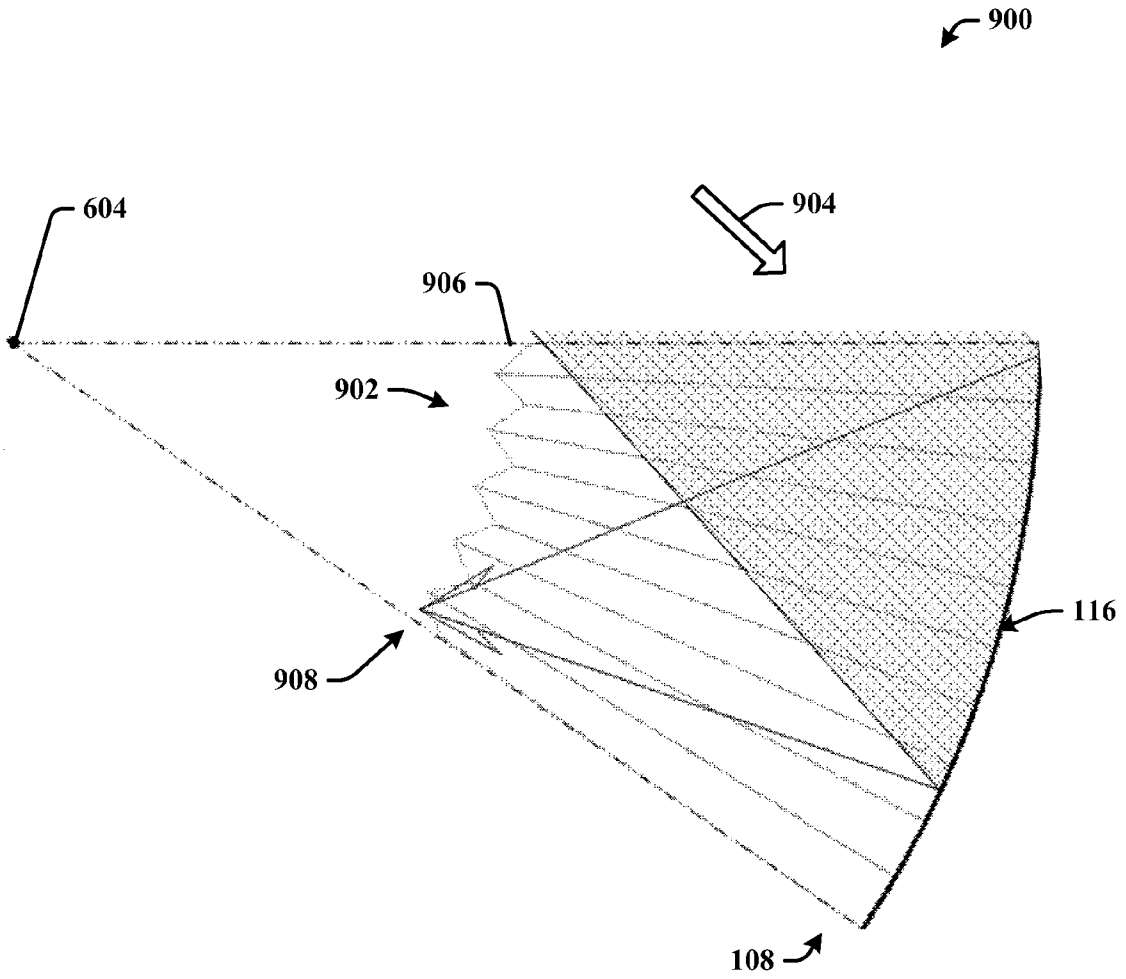

FIG. 9

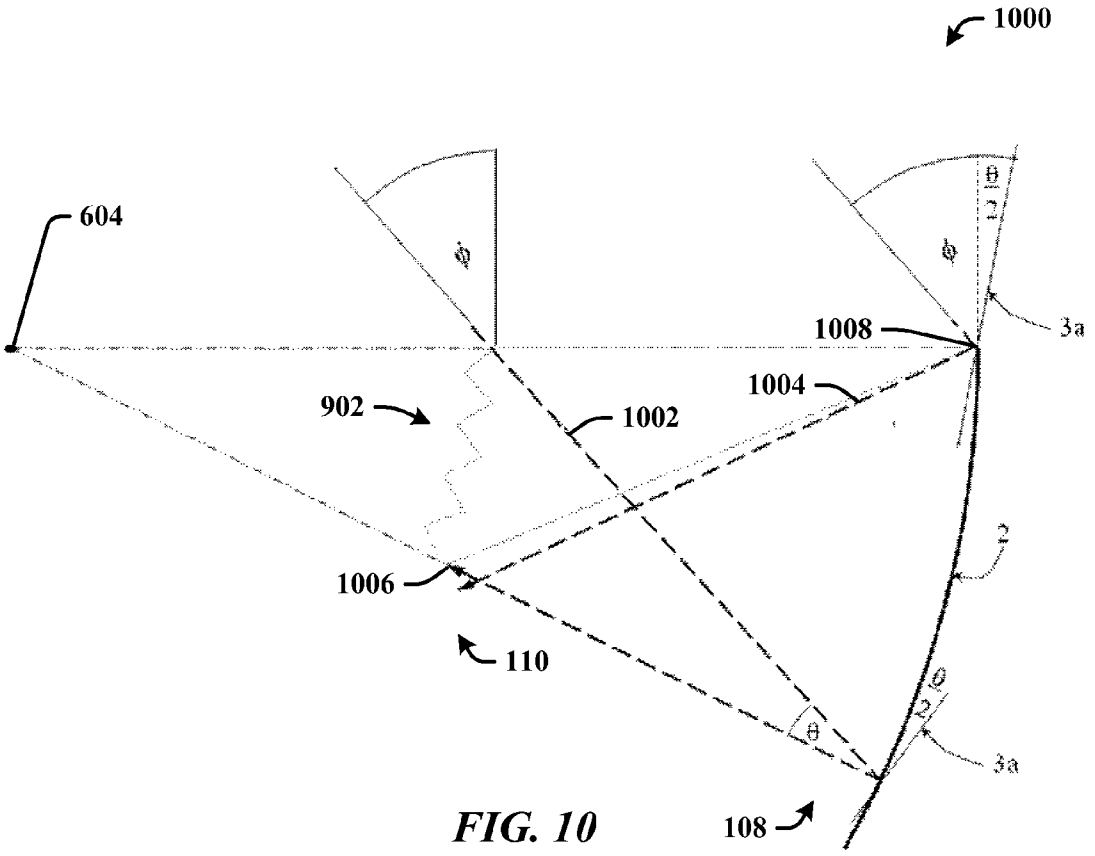

FIG. 10

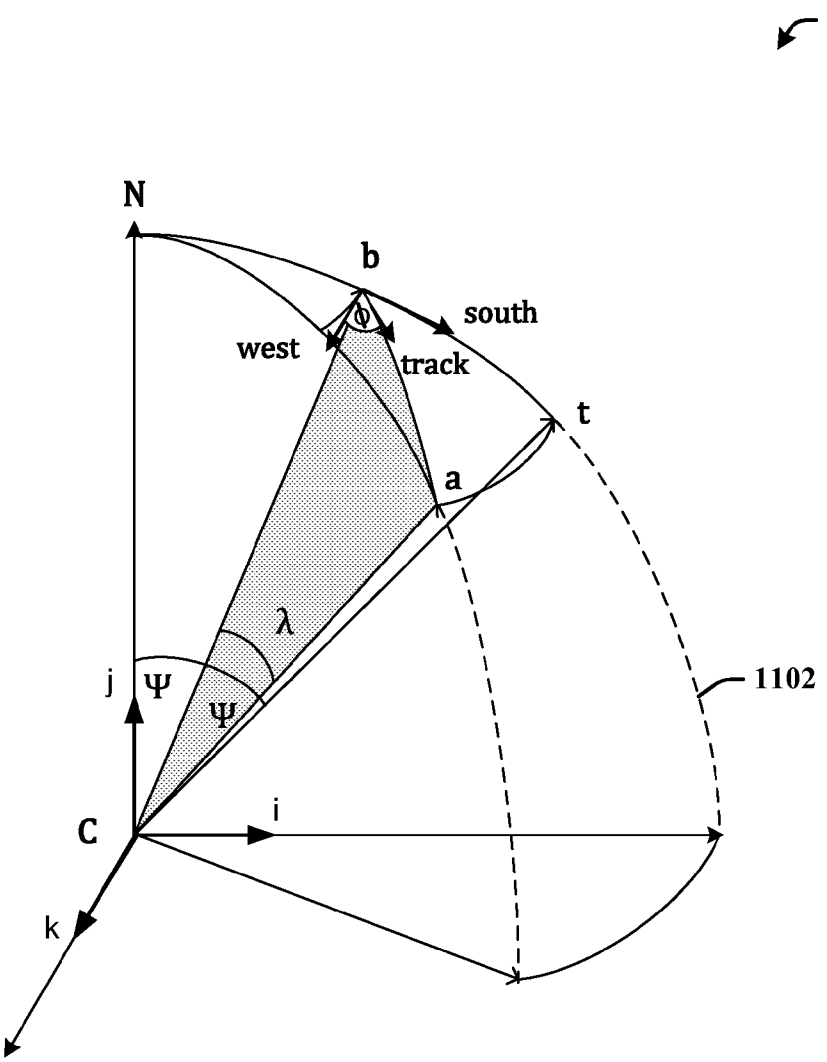

FIG. 11

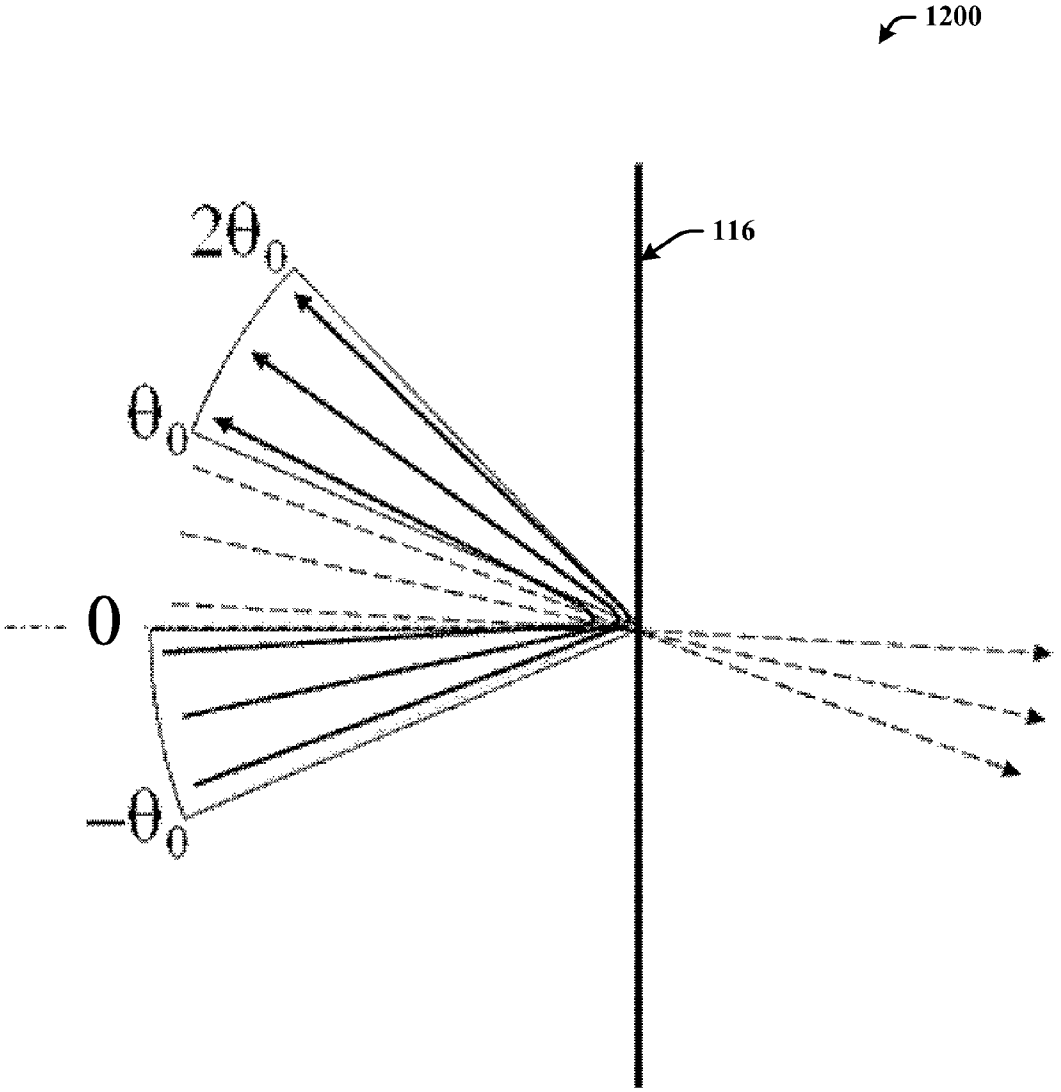

FIG. 12

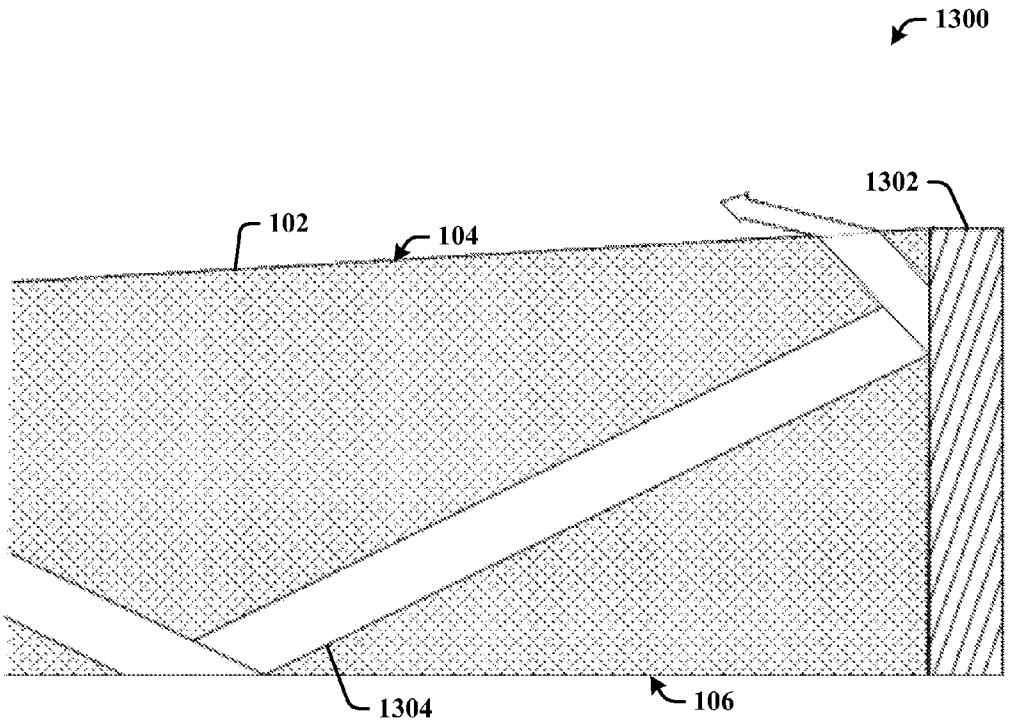

FIG. 13

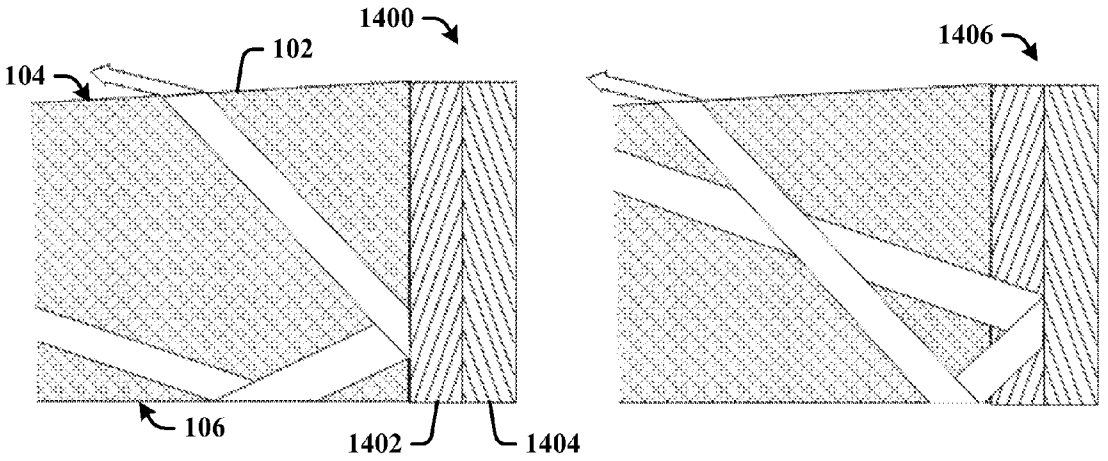

FIG. 14

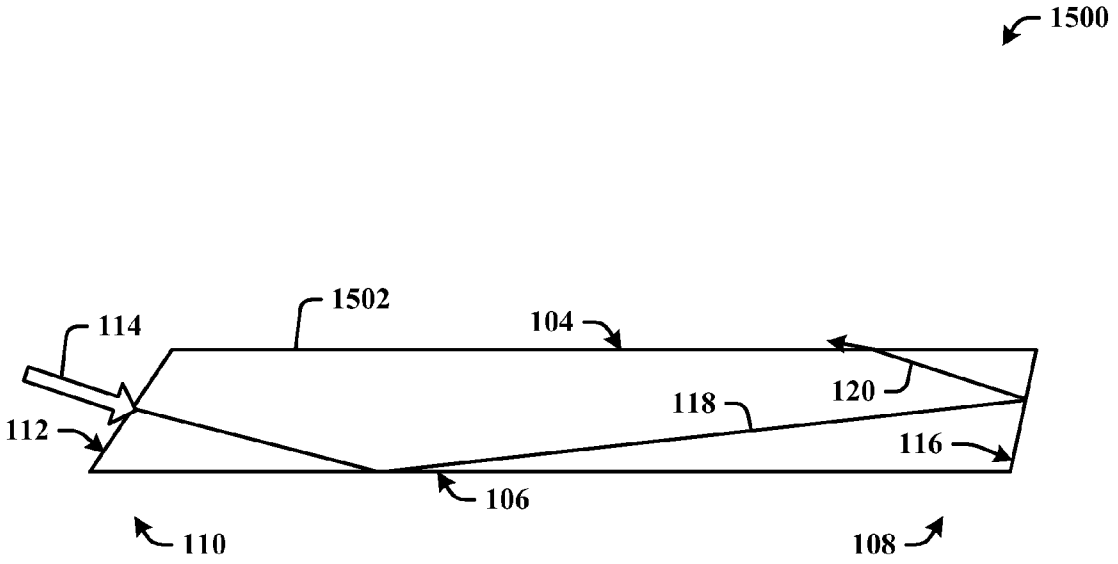

FIG. 15

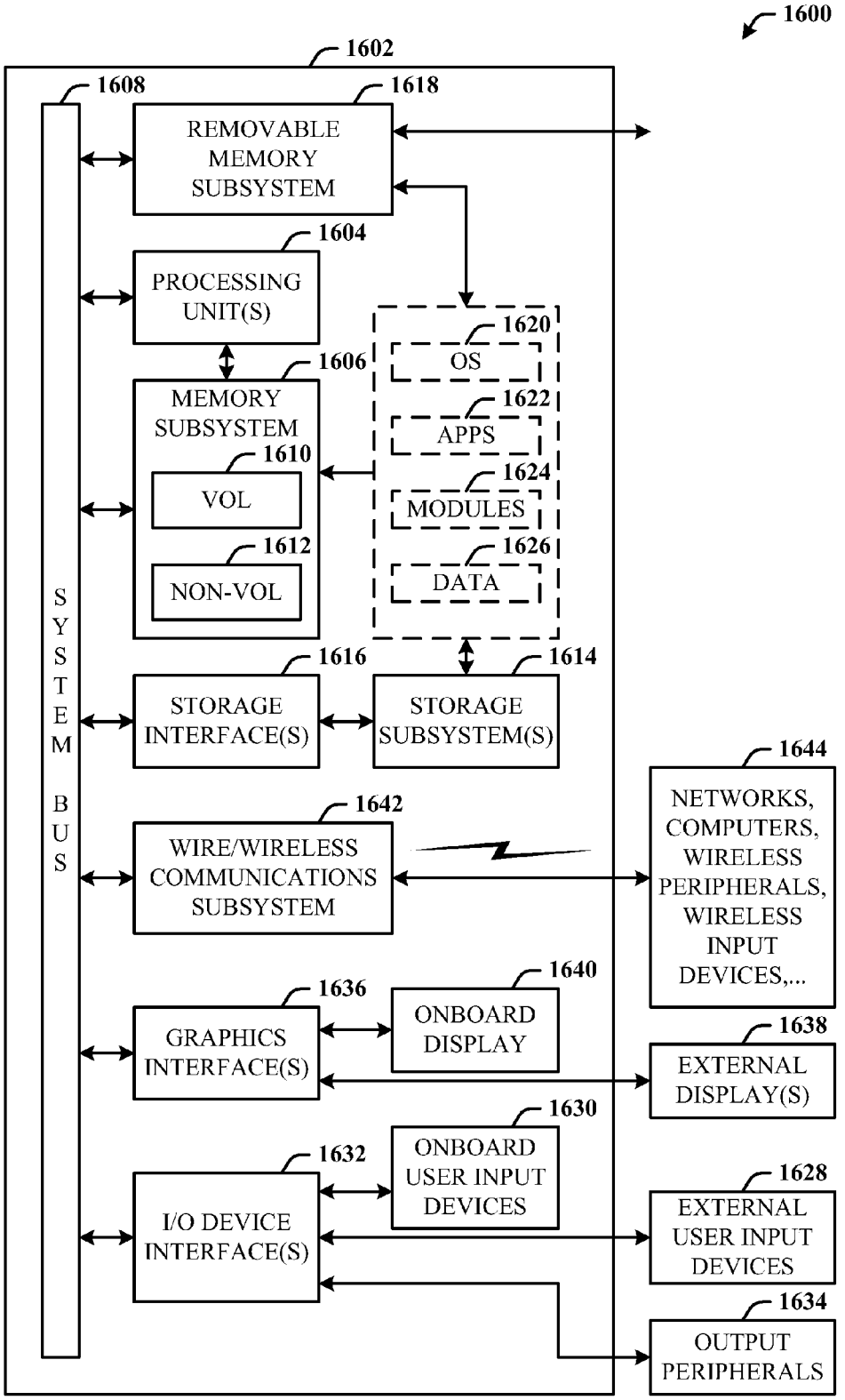
1600
1602
1608
1618
REMOVABLE MEMORY SUBSYSTEM
1604
PROCESSING UNIT(S)
1620
OS
1606
MEMORY SUBSYSTEM
1622
APPS
1610
VOL
1624
MODULES
1612
NON-VOL
1626
DATA
SYSTEM BUS
1616
STORAGE INTERFACE(S)
1614
STORAGE SUBSYSTEM(S)
1644
NETWORKS, COMPUTERS, WIRELESS PERIPHERALS, WIRELESS INPUT DEVICES,...
1642
WIRE/WIRELESS COMMUNICATIONS SUBSYSTEM
1640
1636
ONBOARD DISPLAY
GRAPHICS INTERFACE(S)
1638
EXTERNAL DISPLAY(S)
1630
1632
ONBOARD USER INPUT DEVICES
1628
I/O DEVICE INTERFACE(S)
EXTERNAL USER INPUT DEVICES
1634
OUTPUT PERIPHERALS

FIG. 16

FLAT PANEL LENS

BACKGROUND

[0001] It is well known that rays emanating from a point in the focal plane of a lens are collimated and that parallel rays incident on a lens are concentrated to a point. A flat panel lens collimates rays emanating from a point but needs no volume for rays to fan out between the point and the plane of ray collimation. In a flat panel lens, however, the point and plane periphery are separate and there is an undesirable margin inbetween the point and plane periphery.

[0002] There is space between an ordinary lens and each of its focal planes and this can also make optical systems bulky. One proposed solution discloses a flat panel lens that collimates rays emanating from a point, or from a point to a flat panel lens, within a slim tapered light guide. The focal point and exit surface are approximately coplanar but displaced from one another because a slab of light guide is disposed between the two in order that rays can fan-out from the focal point to the exit surface.

[0003] Rear projection televisions are normally bulky because space is required between the video projector and diffusive screen in order that the picture fills the screen. The space may be replaced by a flat panel lens but there is no need to collimate the light because the screen necessarily destroys collimation. Thus, a simple tapered optical waveguide with uniform cross-section can suffice. However, a slab of light guide within which rays from the projector fan-out forms a blank margin on the screen where users would rather want to see the picture fill the screen.

[0004] Alternatively, a pair of prisms can be used to fold the slab behind the screen, but the slab, tapered waveguide and prisms must be carefully aligned and this has the potential to be costly. In yet another attempted solution, the direction of rays may be reversed in all linear optical systems and a tapered light guide may be used to remove the space between a camera and the object being photographed. However, a slab of light guide is again required, this time so that rays can fan-in. Although the resulting margin may be removed with folding prisms, these again, can be very costly.

SUMMARY

[0005] The following presents a simplified summary in order to provide a basic understanding of some novel embodiments described herein. This summary is not an extensive overview, and it is not intended to identify key/critical elements or to delineate the scope thereof. Its sole purpose is to present some concepts in a simplified form as a prelude to the more detailed description that is presented later.

[0006] Disclosed is a flat panel lens as a tapered light guide that has minimal or no margin. No folding prisms are utilized and the light guide can be formed from a single piece of transparent material. In one implementation, the tapered light guide includes a thin end, and a thick end of which is a bevelled mirror or an optical equivalent. The bevel is such that rays injected through a point at the thin end emerge collimated from one of the light guide surfaces, and that collimated rays injected at an appropriate angle through one of the light guide surfaces emerge from a point at the thin end.

[0007] The light guide finds particular application to flat panel displays and displays that provide direct human tactile interaction (independent of conventional input devices such as mice and keyboards, for example), cameras, and projection televisions, to name just a few. The tapered light guide can be fabricated as a single piece, by extrusion, injection molding, or the combination/variation of extrusion and injection molding, as well as other commonly known techniques.

[0008] To the accomplishment of the foregoing and related ends, certain illustrative aspects are described herein in connection with the following description and the annexed drawings. These aspects are indicative of the various ways in which the principles disclosed herein can be practiced, all aspects and equivalents of which are intended to be within the scope of the claimed subject matter. Other advantages and novel features will become apparent from the following detailed description when considered in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** illustrates a lens system the characteristics and dimensions of which reduce or eliminate the margin on a display.

[0010] FIG. **2** illustrates examples of light injected into the receiving face of the light guide at different angles from a light source and the deflected light from the reflecting face at the thick end.

[0011] FIG. **3** illustrates an alternative light guide having a light guide with a receiving face oriented at a different angle suitable to provide specular light that exits the first guide according to the critical angle.

[0012] FIG. **4** illustrates that rays injected into the center of the thin end of the light guide can fan out to the width of the light guide.

[0013] FIG. **5** illustrates that the reflecting face can be configured as a Fresnellated surface of alternate mirror angles.

[0014] FIG. **6** illustrates an alternative embodiment of a light guide having curved surfaces in which all rays undergo the same number of reflections before exit.

[0015] FIG. **7** illustrates a light guide that provides a smooth transition from the tapered section to a section with parallel sides before light rays encounter the reflecting face.

[0016] FIG. **8** illustrates that the radius of curvature of the thick end can be twice the length of the light guide.

[0017] FIG. **9** illustrates a diagram that employs a representation of duplicate light guides in which the thick end of each is curved according to the implementations described in FIG. **7** and FIG. **8**.

[0018] FIG. **10** illustrates a technique for deriving a minimum thickness of the light guide when the light guide surfaces are flat.

[0019] FIG. **11** illustrates a technique for drawing FIG. **10** on a spherical surface so that rays entering either end of the light guide surface meet as when leaving the thin end.

[0020] FIG. **12** illustrates the optical properties that can be employed for the reflecting face at the thick end.

[0021] FIG. **13** illustrates a lens system where the reflecting face can be replaced by a Bragg reflector.

[0022] FIG. **14** illustrates that the reflecting face can be replaced by a pair of Bragg reflectors.

[0023] FIG. **15** illustrates an alternative embodiment of a lens system where a light guide uses a graded index between the thin end and the thick end.

[0024] FIG. **16** illustrates a block diagram of a computing system operable to employ the lens system in accordance with the disclosed architecture.

DETAILED DESCRIPTION

[0025] Disclosed is a wedge (or tapered) light guide where the point source of light is placed at the thin end and the thick end is a reflector tilted so as to reduce the angle between rays and the plane of the light guide. The reflector can include a zig-zag (or Fresnellated) surface. The thick end can be curved about a point distant from the thin end of the wedge by one wedge length in a direction parallel to the axis of taper. Additionally, the thick end can be twice as thick as the thin end. The thickness profile of the wedge is proportional to sin [(z+L)/kL], where z is distance from the thin end, L is the length of the wedge, and k is a constant.

[0026] Reference is now made to the drawings, wherein like reference numerals are used to refer to like elements throughout. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding thereof. It may be evident, however, that the novel embodiments can be practiced without these specific details. In other instances, well known structures and devices are shown in block diagram form in order to facilitate a description thereof. The intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the claimed subject matter.

[0027] FIG. **1** illustrates a lens system **100** the characteristics and dimensions of which reduce or eliminate the margin on a display. The lens system **100** includes a wedge-shaped light guide **102** having a first guide surface **104** and second guide surface **106** that tapers from a thick end **108** to a thin end **110**. The light guide **100** also includes a receiving face **112** at the thin end **110** for receiving light **114** injected into the light guide **102**, and a reflecting face **116** (also referred to as a bevelled or tilted mirror, and reflecting surface) at the thick end **108** of the light guide **102** for deflecting incident light **118** back to the first guide surface **104** (and possibly the second guide surface **106**), the deflected incident light **120** (or specular light) exiting the first guide surface **104** (or display surface) before reaching the receiving face **112**.

[0028] FIG. **2** illustrates examples **200** of light injected into the receiving face **112** of the light guide **102** at different angles from a light source **202** and the deflected light from the reflecting face **116** at the thick end **108**. The reflecting face **116** (the bevelled mirror) causes rays injected at the thin end **110** to be deflected in such a way as to reach a critical angle (the angle at which the light will depart the light guide **102** rather than reflect internally) and depart the tapered waveguide (the light guide **102**) at a point dependent on the associated angle of injection by the light source **202**. The reflecting face **116** deflects incident rays so that the deflected incident rays return toward the thin end **110** but with a much reduced angle relative to an axis **204** perpendicular to a plane **206** of the light guide **102**. After deflection, the diminishing thickness encountered in the direction of the thin end **110** by each ray causes the ray angle to reduce until the ray angle is less than the critical angle (for the particular material of the light guide **102**), at which point the ray emerges from a guide surface (first guide surface **104** and/or second guide surface **106**) of the light guide **102**.

[0029] In the top example **200**, the injected ray from the light source **202** enters the guide **102** at a low angle, deflects off the reflecting surface **116** and returns nearly to the receiving face **112** before exiting the first guide surface **102**. In the middle example **200**, the injected ray from the light source **202** enters the guide **102** at a higher angle than in the top example, deflects off the reflecting surface **116** and returns to exit the light guide **102** near the middle before reducing to the critical angle to exit the first guide surface **102**. In the bottom example **200**, the injected ray from the light source **202** enters the light guide **102** at a still higher angle than in the middle example, deflects off the reflecting surface **116** and returns to exit the light guide **102** at the first surface **102** near the reflecting face **116**. Thus, it is easy to see that by adjusting the angle at which the light source injects the light into the receiving face **112**, the margin can be reduced or eliminated entirely when viewed from the first surface **104**.

[0030] FIG. **3** illustrates an alternative light guide system **300** having a light guide **302** with a receiving face **304** oriented at a different angle suitable to provide specular light that exits the first guide surface **104** according to the critical angle. The reflecting face **116** (the bevelled mirror) causes rays injected into the receiving face **304** at the thin end **110** to be deflected in such a way as to reach the critical angle and depart the tapered waveguide (the light guide **302**) at a point dependent on the associated angle of injection by the light source **202**. The reflecting face **116** deflects incident rays so that the deflected incident rays (or specular rays) return toward the thin end **110** but with a much reduced angle relative to an axis **306** perpendicular to a plane **308** of the light guide **302**. After reflection, the diminishing thickness encountered in the direction of the thin end **110** by each ray causes the ray angle to reduce until the ray angle is less than the critical angle, at which point the ray emerges from a guide surface (the first guide surface **104** and/or second guide surface **106**) of the light guide **302**.

[0031] FIG. **4** illustrates that rays **400** injected into the center of the thin end **110** the light guide **102** can fan out to the width of the light guide **102** so that after deflecting off the reflecting face **116** (also called the bevelled mirror) at the thick end **108**, the rays **400** illuminate the whole area (the entirety) of a front surface **402** (similar to the first guide surface **104**) of the light guide **102**. Light exiting the whole area of the front surface **402** is represented by ray arrows exiting near each of the four corners of the front surface **402**. There is therefore no need for a blank margin within which rays can fan out, as in conventional systems in the lower half of the light guide **102** near the light source **202**.

[0032] It has been shown conventionally that for a smooth light guide, the product of light guide thickness with the cosine of the ray angle relative to the perpendicular of the light guide is a constant number. It follows that thickness times the sine of the ray angle relative to the plane of the light guide is also a constant number. The sine of a small angle is approximately proportional to the angle itself, so it can be said that the product of the thickness with the ray angle itself is approximately constant. Consider that light rays are injected into the thick end **108** into the light guide **102** by the light source **202** (e.g., laser, LED) at a uniformly distributed range of angles between zero and the critical angle, and that the light guide **102** gradually tapers to half its input thickness (e.g., at the thin end **110**). The angle of rays reaching the thin end **110** will have doubled so half of the injected rays have exceeded the critical angle and are no longer guided.

[0033] Instead, as in the disclosed technique, rays are injected at the thin end **110** and the angles of the rays **400** will all be less than half the critical angle at the thick end **108**. An

appropriately angled reflecting face **116** reflects the rays **400** so that all rays **400** are returned at greater than half the critical angle. Thus, all rays **400** leave the light guide **102** before reaching the thin end **110**. Therefore, in one implementation, the thick end **108** of the light guide **102** is at or about twice the thickness of the thin end **110**.

[0034] The three rays shown in the top, middle and bottom examples **200** of FIG. **2** are all incident on the reflecting face **116** at the thick end **108** from the left-hand side in the light guide **102**. Rays will, however, also be incident from the right-hand side and these rays will propagate back down the light guide **102** and be lost to the system through the thin end **110**, so there can be gaps in the projected image.

[0035] FIG. **5** illustrates that the reflecting face **116** can be configured as a Fresnellated surface **500** of alternate mirror angles. The Fresnellated surface **500** can be embossed on the thick end **108** to ensure that for any incident ray **502**, a portion **504** of the ray **502** is lost, but a specular portion **506** goes on to form an image **508** so that the image is uniform and formed free of gaps (margins). Accordingly, the Fresnellated surface **500** for the reflecting face **116** on the thick end **108** comprises pairs of reflecting planes (**510** and **512**) the normals of which share the same component resolved in the plane of the light guide **102** but have equal and opposite components perpendicular to the plane of the light guide **102**.

[0036] Discontinuities in an image projected through a tapered light guide with straight sides will form at the point where a small change in ray injection angle causes the ray to undergo an extra reflection. The lower part of the projected image on the front surface **402** in FIG. **4** is closer to the light source **202** (e.g., projector) than the upper part, so the projected image can be subject to keystone distortion (a distortion in image dimensions that makes the image look similar to a trapezoid) because the reflecting face **116** at the thick end **108** is flat.

[0037] FIG. **6** illustrates an alternative embodiment of a light guide **600** having curved surfaces in which all rays undergo the same number of reflections before exit. The reflecting face **116** is curved about an axis **602** perpendicular to the plane of the light guide **600** and with a radius of curvature equal to twice the length of the light guide **600**. Rays no longer fan out after reflection so keystone distortion is eliminated. However, it can be desirable that the edges of a display be straight. Thus, the reflecting face **116** may instead be a Fresnel surface and the collimating action of this may be integrated with the actions of the reflecting planes **510** and **512** (of FIG. **5**) into a single prismatic surface.

[0038] The surface provided by curving the reflecting face **116** is approximately cylindrical. A disadvantage of cylindrical mirrors (or surfaces) is the introduction of an astigmatism that can degrade resolution. This is resolved as follows.

[0039] FIG. **7** illustrates a light guide **700** that provides a smooth transition from the tapered section **702** to a section **704** with parallel sides before light rays encounter the reflecting face **116**. The reflecting face **116** at the end of the light guide **700** is curved with a uniform radius of curvature such that a first corner **706** defined by the first guide surface **104** and the curved reflecting face **116**, and a second corner **708** defined by the second guide surface **106** and the curved reflecting face **116**, both are right angles. When employing the Fresnel surface **500** of FIG. **5**, the reflecting planes (**510** and **512**) conform to this curvature so that the angle made by each of the planes (**510** and **512**) relative to the reflecting face **116** is constant.

[0040] FIG. **8** illustrates that the radius of curvature **800** of the thick end **108** can be twice the length of the light guide **102**. As described herein above in one implementation, it can be optimal for the thick end **108** of the light guide **102** to be double the thickness of the thin end **110**. Moreover, since the light guide **102** has flat surfaces (the first guide surface **104** and second guide surface **106**), the radius of curvature for the thick end **108** equals twice the length of the light guide **102**. This means that the reflecting face **116** has the same radius of curvature about the axis **604** depicted in FIG. **6** as indicated about axis **602** in order to minimize keystone distortion. The combined curvature of the thick end **108** is therefore spherical, in which case the reflecting face **116** introduces no astigmatism and resolution is not degraded.

[0041] The path of a ray through a light guide can be found by tracing the ray alternately to upper and lower surfaces and calculating the angle of reflection off each surface; however, this can be laborious and poorly informative. If the light guide has flat surfaces, it is simpler and optically equivalent to draw a ray straight through a stack of duplicates of the tapered light guide until the ray crosses an intersection at less than the critical angle, when the ray will in reality emerge into air. It is also permissible to use a reverse approach by drawing the ray in reverse; in other words, rather than injecting the ray at one end of the light guide and tracing ray progression until it emerges from a surface, the ray can be traced from the surface of a stack of light guides back to a light guide end with the proviso that the ray leaves the surface at the critical angle and never exceeds the critical angle.

[0042] FIG. **9** illustrates such a diagram **900** that employs a representation of duplicate light guides **902** in which the thick end **108** of each is curved according to the implementations described in FIG. **7** and FIG. **8**. Using the reverse approach described above, incident rays **904** imposed on what can actually be an exit surface **906** (similar to first guide surface **104**) reflect off the reflecting face **116** of thick end **108**. The duplicate light guides **902** at the thick end **108** combine into a curve of constant radius, thereby concentrating parallel rays approximately to a point **908** at a distance equal to half the radius of curvature of the curve.

[0043] If the thick end **108** were perfectly smooth, this point **908** would be at the thin end **110** of the top light guide of the duplicate light guides **902**, but the action of the Fresnel planes (**510** and **512** of FIG. **5**) is to deflect half of each ray such that the point of focus of the deflected halves is at the thin end **110** of one of the duplicates **902** lower in the stack. In an optimum implementation, all rays undergo the same number of reflections between entrance and exit. FIG. **9** demonstrates that this is an inherent property of the embodiment illustrated because each ray crosses the same number of light guide interfaces as any other ray.

[0044] Perpendicular to the plane of FIG. **9**, rays traced from the thin end **110** are approximately collimated by reflection off the spherical surface of the reflecting face **116**, so an image projected through the light guide experiences little distortion. Collimated rays have no skew, so the projected image exhibits uniformity.

[0045] Additionally, rays can be injected into the receiving face at the thin end of the light guide so as to emerge from any point on the display surface, thereby reducing, or eliminating margins entirely. That the sides of the light guides have no curvature helps preserve the resolution of an image projected through the light guide. Moreover, this also means that the lens system is simple to make.

[0046] To make the tapered light guide surfaces (e.g., first guide surface **104** and second guide surface **106**), the base of a polishing machine can be tilted, a sheet of high transparency glass waxed on top and polished flat. To make the spherically curved reflecting face **116** (bevelled mirror), several such tapered light guides can be waxed together in a stack and a sphere polished on the end as if on a conventional lens surface. The Fresnellated planes (**510** and **512**) can then be cast on a film, stretched over the spherical reflecting face **116**, and then glued on.

[0047] FIG. **10** illustrates a technique **1000** for deriving a minimum thickness of the light guide when the light guide surfaces are flat. A spherical curvature on the reflecting face **116** reflects parallel rays not to a point but to a spot of finite thickness, and the light guide can be designed to be no thinner than the size of the spot. FIG. **10** applies geometry to FIG. **9** to show how this minimum thickness can be calculated. Two rays (**1002** and **1004**) are shown, and the point of exit **1006** of ray **1002** is proximate the thin end **110**, while the point of exit **1006** of ray **1004** is proximate the thick end **108**. All rays (**1002** and **1004**) are at the critical angle ϕ just before exiting. Tracing of both rays (**1002** and **1004**) backwards at this angle is performed straight through the stack of light guide duplicates **902** until the rays (**1002** and **1004**) meet the thick end **108**.

[0048] When employing the Fresnel planes (**510** and **512**), after reflection off the Fresnel plane **510** at the thick end **108**, tracing of the ray **1002** back to the thin end **110** parallel to the plane of the light guide duplicate can be performed. The reflected part of ray **1002** is at some angle θ to the incident part of the ray, which angle θ can be calculated, while Fresnel plane **510** is at an angle $\theta/2$ to the spherical curvature of the reflecting face **116**.

[0049] Ray **1004** reflects off the same Fresnel plane **510**. Thus, the angle of the reflected part of ray **1004** can be calculated. By symmetry, this angle equals θ, if ray **1002** and ray **1004** are to meet at the thin end **110**. Geometry calculations show that if the critical angle ϕ equals 42 degrees, θ equals 21 degrees, while ray **1004** instead is reflected at 24 degrees to the wedge surface (e.g., the first guide surface **104**), a difference of about three degrees.

[0050] Focus can be improved if very thin light guides are to be made. However, the symmetry of FIG. **9** indicates that the thick end **108** be a simple curve. Rather than altering the geometry of the thick end **108**, the sides of the tapered light guide can be curved and many such light guides joined in the manner of FIG. **9** will map onto a spheroid, similar to the peel slices of a segmented orange. The surface curvature desired of a very thin tapered light guide can be found by drawing FIG. **10** on a spheroid whose radius of curvature is such that all rays reflected off the thick end **108** meet at a point. This is now described.

[0051] FIG. **11** illustrates a technique **1100** for drawing FIG. **10** on a spherical surface so that rays entering either end of the light guide surface meet as when leaving the thin end **110**. FIG. **11** depicts a section of a sphere **1102**, having a North Pole N, where the ray **1002** of FIG. **10** moves from position b at a latitude of ψ degrees to the North Pole N at a Southwesterly angle ϕ according to a vector called track. The ray **1002** stops when at a latitude of 2ψ, the final position denoted by vector a. The initial direction of the ray **1002** was t, and the ray **1002** moved along a great circle route, so a can be expressed as a linear sum of b and t. If the arc ba of the great circle route has angle λ relative to the center C of the sphere, then,

$$a = \cos\lambda b + \sin\lambda t$$

$$= \cos\lambda \begin{pmatrix} \sin\psi \\ \cos\psi \\ 0 \end{pmatrix} + \sin\lambda \begin{pmatrix} \sin\phi\cos\psi \\ -\sin\phi\sin\psi \\ \cos\phi \end{pmatrix}$$

[0052] Position a is at a latitude of 2ψ so the j component of a is equal to $\cos 2\psi$:

$$a_j = \cos 2\psi \sqrt{1-\sin^2\lambda\cos\psi-\sin\lambda\sin\phi\sin\psi}$$

So

$$(1-\sin^2\lambda)\cos^2\psi = \cos^2 2\psi + \sin^2\lambda \sin^2\phi \sin^2\psi + 2\cos 2\psi \sin\lambda \sin\phi \sin\psi$$

And,

$$0 = (\cos^2 2\psi - \cos^2\psi) + (2\cos 2\psi \sin\phi \sin\psi)\sin\lambda + (\sin^2\phi \sin^2\psi + \cos^2\psi)\sin^2\lambda$$

[0053] This is a quadratic equation solvable to obtain $\sin\lambda$; then λ, and then a. The distance moved by the ray **1002** is λ times the radius of the sphere, but it is desirable to know θ, the direction of the ray **1002** as it reaches position a. This can be determined by calculating the normal n, to the great circle route, which the ray **1002** has just travelled; n is perpendicular to both b and t, thus:

$$n = b \times t = \begin{pmatrix} \sin\psi \\ \cos\psi \\ 0 \end{pmatrix} \times \begin{pmatrix} \sin\phi\cos\psi \\ -\sin\phi\sin\psi \\ \cos\phi \end{pmatrix} = \begin{pmatrix} \cos\psi\cos\phi \\ -\sin\psi\cos\phi \\ -\sin\phi \end{pmatrix}$$

[0054] A vector that is perpendicular to the circle of longitude through the ray's final position can be obtained by calculating j×a:

$$j \times a = \cos\lambda \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \sin\psi \\ \cos\psi \\ 0 \end{pmatrix} + \sin\lambda \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \sin\phi\cos\psi \\ -\sin\phi\sin\psi \\ \cos\phi \end{pmatrix}$$

$$= \cos\lambda \begin{pmatrix} 0 \\ 0 \\ -\sin\psi \end{pmatrix} + \sin\lambda \begin{pmatrix} \cos\phi \\ 0 \\ -\sin\phi\cos\psi \end{pmatrix}$$

$$= \cos\lambda \begin{pmatrix} 0 \\ 0 \\ -\sin\psi \end{pmatrix} + \sin\lambda \begin{pmatrix} \cos\phi \\ 0 \\ -\sin\phi\cos\psi \end{pmatrix}$$

[0055] Now, θ equals the angle between the line of travel and the line of longitude through a, so angle θ is also equal to the angle between the perpendiculars to both these lines. Hence:

$$\cos\theta = n \cdot \frac{j \times a}{|j \times a|} = \frac{\begin{pmatrix} \cos\psi\cos\phi \\ -\sin\psi\cos\phi \\ -\sin\phi \end{pmatrix} \cdot \begin{pmatrix} \sin\lambda\cos\phi \\ 0 \\ -\cos\lambda\sin\psi - \sin\lambda\sin\phi\cos\psi \end{pmatrix}}{|j \times a|}$$

$$= \frac{\cos\psi\sin\lambda\cos^2\phi + \sin\phi\cos\lambda\sin\psi + \sin\lambda\sin^2\phi\cos\psi}{\sqrt{\sin^2\lambda\cos^2\phi + (\cos\lambda\sin\psi + \sin\lambda\sin\phi\cos\psi)^2}}$$

[0056] By entering this into a spreadsheet, for example, and changing ψ until θ=24 degrees, it transpires that ψ must be 24^0. Since the length L of the wedge (tapered light guide **102**) is equal to the spherical radius R times ψ in radians, it follows that R=L/ψ, which equals 2.39L.

[0057] It remains to calculate the variation of thickness with length L of a wedge drawn on a spherical surface. At latitude β from the North Pole N, the radius of the line of latitude is R sin β. The wedge runs from latitude L/R to 2L/R, so wedge thickness T is proportional to sin [(z+L)/2.39L], where z is the distance along the wedge from the thin end to the thick end. This can be put more generally as the light guide has a thickness profile proportional to sin [(z+L)/kL], where z is distance from the thin end, L is a length of the light guide, and k is a constant.

[0058] The reflecting face **116** of FIG. **5** wastes half the light. The following describes how to eliminate this loss. The loss can be reduced or eliminated if Fresnel planes **510** and **512** are illuminated only by those rays from the thin end which the Fresnel surface reflects so as to emerge from the light guide surface, or similarly, in reverse (from the thin end when the rays are introduced to the light guide surface). For example, if a laser beam scanned by a vibrating mirror is pointed into the thin end, the beam should be switched on when the beam produces a reflection such as specular portion **506** of FIG. **5**, but switched off when the beam produces a reflection such as portion **504**. A photo-sensor can be placed at the thin end and used to switch the laser off whenever the unwanted reflection portion **504** is detected.

[0059] A laser beam may also be scanned by placing a liquid crystal display (LCD) in front of the beam and expressing a diffraction grating on the LCD, and an image can be produced by a superposition of diffraction gratings in a technique known as holographic projection. In this case, loss is minimized by ensuring that the pattern on the LCD is comprised only of gratings which direct light to Fresnel surfaces that do not produce wasted light, such as portion **504**.

[0060] It is well known that light reflected off small facets (e.g., the Fresnel planes **510** and **512**) is subject to aperture diffraction which degrades resolution. Aperture diffraction can be eliminated if a Bragg grating (a structure comprising layers whose refractive index alternates between two values and whose thickness alternates between two values) is used. By suitable choice of thickness and index, it is possible to design the reflecting face **116** so that it reflects monochromatic light over a desired range of angles but is otherwise transparent.

[0061] FIG. **12** illustrates the optical properties that can be employed for the reflecting face **116** at the thick end. A graph **1200** shows that a single reflecting face **116** can be employed for deflecting rays in a range from θ_0 to $2\theta_0$. A second reflecting face can be employed in combination with the reflecting face **116** to process rays in a range from zero to $-\theta_0$.

[0062] FIG. **13** illustrates a lens system **1300** where the reflecting face can be replaced by a Bragg reflector **1302**. The reflector **1302** can therefore be designed to reflect all rays (e.g., ray **1304**) from the lower surface (the second guide surface **106**) of the tapered light guide **102**, but to transmit all those rays from the upper surface (the first guide surface **104**). A conventional planar or Fresnellated mirror can then be embossed beyond the reflector **1302** to reflect rays from the upper surface (e.g., first guide surface **102**).

[0063] FIG. **14** illustrates that the reflecting face can be replaced by a pair of Bragg reflectors **1400**. The two Bragg gratings **1400** may be superposed so that a first grating **1402** reflects rays from the lower surface (the second guide surface **106**) of the light guide **102** and the other rays from the upper side (the first guide surface **104**). Alternatively, the two gratings **1400** may be spatially superposed into a single grating **1406** which performs both functions.

[0064] Color displays are illuminated with red, green and blue (RGB) light so at least three wavelengths can be reflected by the Bragg gratings. These can be the wavelengths of lasers illuminating the video projector in a rear projection television, for example. Three pairs of separate gratings suffice to reflect rays of all three wavelengths incident both from the left-hand and right-hand sides but each pair reflects light only of its own wavelength. It is fortunate that this will happen if the grating is designed for a light guide with a refractive index typical of the most common transparent material as the following paragraph will elaborate.

[0065] A common transparent material such as poly(methyl methacrylate) or PMMA has a refractive index of 1.492 and a critical angle in air of 42 degrees. Thus, a light guide made of this material confines all rays at angles between 0 degrees and 48 degrees to the plane of the light guide. Rays are incident on the thick end at angles less than 24 degrees because the thick end has twice the thickness of the thin end, and all rays are reflected at angles greater than 24 degrees to emerge from the display surface when travelling back toward the thin end. In particular, a ray incident at 24 degrees is reflected at minus 48 degrees as if off a reflecting surface (mirror) angled at minus 12 degrees.

[0066] The Bragg grating which does this has a period equal to the magnitude of the vector sum of the incident and reflected wave vectors, which equals twice cos {[24°−(−48°)]/2}=0.81 per wavelength. A normally incident ray reflects off a grating with two periods per wavelength, so a green ray will pass through a grating designed for blue if the blue to green wavelength ratio is 0.81. The green-to-red wavelength ratio is the same and RGB wavelengths of 430, 532 and 655 nanometers (nm), respectively, will suffice.

[0067] When selected according to these wavelengths, no one wavelength is affected by the gratings designed for the other two wavelengths, so the three pairs of gratings can be superposed in a single film. However, the eye's sensitivity at 655 nm may be poor. In such cases, the critical angle of the light guide can be increased so as to permit a smaller ratio between the wavelengths.

[0068] It may be difficult to apply a Bragg mirror onto the end of a light guide with the desired angular precision. An alternative technique is to create the Bragg grating by directing an ion beam through the side of the light guide. It is well

known that the passage of energetic ions through a polymer can cause bonds to break and the refractive index to change. The ion beam can therefore be used to create the alternating layers of high and low refractive index that constitute a Bragg grating.

[0069] In one general, but non-exhaustive summary, a lens system implementation is provided that comprised a tapered light guide having a display surface and a second guide surface that taper from a thick end to a thin end, the thick end twice in thickness as the thin end; a receiving face at the thin end for receiving light injected into the light guide; and, a reflecting face at the thick end of the light guide for deflecting incident light back to the display surface, the reflecting face tilted to reduce angles of specular rays relative to a plane of the light guide so that the specular rays exit the display surface before reaching the receiving face.

[0070] The tilted reflecting face is a Fresnellated surface and can be curved about a point distant from the thin end by one light guide length in a direction parallel to an axis of taper. The light guide has a thickness profile proportional to sin [(z+L)/kL], where z is distance from the thin end, L is a length of the light guide, and k is a constant. The reflecting face includes one or more reflecting gratings having layers with refractive indexes that alternate between two index values and thickness that alternates between two thickness values, the one or more reflective grating eliminate aperture diffraction.

[0071] The reflecting face is spherically curved according to a uniform radius of curvature, and an angle formed between the display surface and the curved reflecting face is equivalent to an angle formed between the second surface and the curved reflecting face, and the display surface and the second guide surface each form a right angle to the reflecting face at the thick end.

[0072] The injected light entering the receiving face includes rays all of which undergo a same number of reflections prior to exiting the display surface. The reflecting face is comprised of three sets of Bragg gratings for illuminating the display surface using red, green, and blue colors. The light guide can be composed of poly (methyl methacrylate).

[0073] FIG. **15** illustrates an alternative embodiment of a lens system **1500** where a light guide **1502** uses a graded index between the thin end **110** and the thick end **108**. The lens system **1500** includes the light guide **1502** having the first guide surface **104** and second guide surface **106**, which can be parallel, or that taper from the thick end **108** to the thin end **110**. The light guide **1502** also includes the receiving face **112** at the thin end **110** for receiving light **114** injected into the light guide **1502**, and the reflecting face **116** (also referred to as a bevelled or tilted mirror) at the thick end **108** of the light guide **1502** for deflecting incident light **118** back to the first guide surface **104** (and possibly the second guide surface **106**), the deflected incident light **120** (or specular light) exiting the first guide surface **104** before reaching the receiving face **112**. The graded-index characteristic of the light guide **1502** includes a refractive index that decreases with increasing distance from the thin end **110**, such that the light rays follow sinusoidal paths from the thin end **110** to the thick end **108**.

[0074] Referring now to FIG. **16**, there is illustrated a block diagram of a computing system **1600** operable to employ the lens system in accordance with the disclosed architecture. In order to provide additional context for various aspects thereof, FIG. **16** and the following discussion are intended to provide a brief, general description of the suitable computing system **1600** in which the various aspects can be implemented. While the description above is in the general context of computer-executable instructions that can run on one or more computers, those skilled in the art will recognize that a novel embodiment also can be implemented in combination with other program modules and/or as a combination of hardware and software.

[0075] The computing system **1600** for implementing various aspects includes the computer **1602** having processing unit(s) **1604**, a system memory **1606**, and a system bus **1608**. The processing unit(s) **1604** can be any of various commercially available processors such as single-processor, multiprocessor, single-core units and multi-core units. Moreover, those skilled in the art will appreciate that the novel methods can be practiced with other computer system configurations, including minicomputers, mainframe computers, as well as personal computers (e.g., desktop, laptop, etc.), hand-held computing devices, microprocessor-based or programmable consumer electronics, and the like, each of which can be operatively coupled to one or more associated devices.

[0076] The system memory **1606** can include volatile (VOL) memory **1610** (e.g., random access memory (RAM)) and non-volatile memory (NON-VOL) **1612** (e.g., ROM, EPROM, EEPROM, etc.). A basic input/output system (BIOS) can be stored in the non-volatile memory **1612**, and includes the basic routines that facilitate the communication of data and signals between components within the computer **1602**, such as during startup. The volatile memory **1610** can also include a high-speed RAM such as static RAM for caching data.

[0077] The system bus **1608** provides an interface for system components including, but not limited to, the memory subsystem **1606** to the processing unit(s) **1604**. The system bus **1608** can be any of several types of bus structure that can further interconnect to a memory bus (with or without a memory controller), and a peripheral bus (e.g., PCI, PCIe, AGP, LPC, etc.), using any of a variety of commercially available bus architectures.

[0078] The computer **1602** further includes storage subsystem(s) **1614** and storage interface(s) **1616** for interfacing the storage subsystem(s) **1614** to the system bus **1608** and other desired computer components. The storage subsystem (s) **1614** can include one or more of a hard disk drive (HDD), a magnetic floppy disk drive (FDD), and/or optical disk storage drive (e.g., a CD-ROM drive DVD drive), for example. The storage interface(s) **1616** can include interface technologies such as EIDE, ATA, SATA, and IEEE 1394, for example.

[0079] One or more programs and data can be stored in the memory subsystem **1606**, a removable memory subsystem **1618** (e.g., flash drive form factor technology), and/or the storage subsystem(s) **1614**, including an operating system **1620**, one or more application programs **1622**, other program modules **1624**, and program data **1626**. Generally, programs include routines, methods, data structures, other software components, etc., that perform particular tasks or implement particular abstract data types. All or portions of the operating system **1620**, applications **1622**, modules **1624**, and/or data **1626** can also be cached in memory such as the volatile memory **1610**, for example. It is to be appreciated that the disclosed architecture can be implemented with various commercially available operating systems or combinations of operating systems (e.g., as virtual machines).

[0080] The storage subsystem(s) **1614** and memory subsystems (**1606** and **1618**) serve as computer readable media

for volatile and non-volatile storage of data, data structures, computer-executable instructions, and so forth. Computer readable media can be any available media that can be accessed by the computer **1602** and includes volatile and non-volatile media, removable and non-removable media. For the computer **1602**, the media accommodate the storage of data in any suitable digital format. It should be appreciated by those skilled in the art that other types of computer readable media can be employed such as zip drives, magnetic tape, flash memory cards, cartridges, and the like, for storing computer executable instructions for performing the novel methods of the disclosed architecture.

[0081] A user can interact with the computer **1602**, programs, and data using external user input devices **1628** such as a keyboard and a mouse. Other external user input devices **1628** can include a microphone, an IR (infrared) remote control, a joystick, a game pad, camera recognition systems, a stylus pen, touch screen, gesture systems (e.g., eye movement, head movement, etc.), and/or the like. The user can interact with the computer **1602**, programs, and data using onboard user input devices **1630** such a touchpad, microphone, keyboard, etc., where the computer **1602** is a portable computer, for example. These and other input devices are connected to the processing unit(s) **1604** through input/output (I/O) device interface(s) **1632** via the system bus **1608**, but can be connected by other interfaces such as a parallel port, IEEE 1394 serial port, a game port, a USB port, an IR interface, etc. The I/O device interface(s) **1632** also facilitate the use of output peripherals **1634** such as printers, audio devices, camera devices, and so on, such as a sound card and/or onboard audio processing capability.

[0082] One or more graphics interface(s) **1636** (also commonly referred to as a graphics processing unit (GPU)) provide graphics and video signals between the computer **1602** and external display(s) **1638** (e.g., LCD, plasma) and/or onboard displays **1640** (e.g., for portable computer). The graphics interface(s) **1636** can also be manufactured as part of the computer system board. The external display(s) **1638** and/or onboard display **1640** can include the lens system disclosed herein.

[0083] The computer **1602** can operate in a networked environment (e.g., IP) using logical connections via a wire/wireless communications subsystem **1642** to one or more networks and/or other computers. The other computers can include workstations, servers, routers, personal computers, microprocessor-based entertainment appliance, a peer device or other common network node, and typically include many or all of the elements described relative to the computer **1602**. The logical connections can include wire/wireless connectivity to a local area network (LAN), a wide area network (WAN), hotspot, and so on. LAN and WAN networking environments are commonplace in offices and companies and facilitate enterprise-wide computer networks, such as intranets, all of which may connect to a global communications network such as the Internet.

[0084] When used in a networking environment the computer **1602** connects to the network via a wire/wireless communication subsystem **1642** (e.g., a network interface adapter, onboard transceiver subsystem, etc.) to communicate with wire/wireless networks, wire/wireless printers, wire/wireless input devices **1644**, and so on. The computer **1602** can include a modem or has other means for establishing communications over the network. In a networked environment, programs and data relative to the computer **1602** can be stored in the remote memory/storage device, as is associated with a distributed system. It will be appreciated that the network connections shown are exemplary and other means of establishing a communications link between the computers can be used.

[0085] The computer **1602** is operable to communicate with wire/wireless devices or entities using the radio technologies such as the IEEE 802.xx family of standards, such as wireless devices operatively disposed in wireless communication (e.g., IEEE 802.11 over-the-air modulation techniques) with, for example, a printer, scanner, desktop and/or portable computer, personal digital assistant (PDA), communications satellite, any piece of equipment or location associated with a wirelessly detectable tag (e.g., a kiosk, news stand, restroom), and telephone. This includes at least Wi-Fi (or Wireless Fidelity) for hotspots, WiMax, and Bluetooth™ wireless technologies. Thus, the communications can be a predefined structure as with a conventional network or simply an ad hoc communication between at least two devices. Wi-Fi networks use radio technologies called IEEE 802.11x (a, b, g, etc.) to provide secure, reliable, fast wireless connectivity. A Wi-Fi network can be used to connect computers to each other, to the Internet, and to wire networks (which use IEEE 802.3-related media and functions).

[0086] The illustrated aspects can also be practiced in distributed computing environments where certain tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules can be located in local and/or remote storage and/or memory system.

[0087] What has been described above includes examples of the disclosed architecture. It is, of course, not possible to describe every conceivable combination of components and/or methodologies, but one of ordinary skill in the art may recognize that many further combinations and permutations are possible. Accordingly, the novel architecture is intended to embrace all such alterations, modifications and variations that fall within the spirit and scope of the appended claims. Furthermore, to the extent that the term "includes" is used in either the detailed description or the claims, such term is intended to be inclusive in a manner similar to the term "comprising" as "comprising" is interpreted when employed as a transitional word in a claim.

What is claimed is:

1. A lens system, comprising:

a tapered light guide having first and second surfaces that taper from a thick end to a thin end;

a receiving face at the thin end for receiving light injected into the light guide; and

a reflecting face at the thick end of the light guide for deflecting incident light back to the first and second surfaces, the deflected light exiting the first surface before reaching the receiving face.

2. The system of claim **1**, wherein the reflecting face is formed at an angle such that the injected light deflected off the reflecting face exits the first surface or the second surface as collimated light.

3. The system of claim **1**, wherein the reflecting face is formed at an angle such that collimated light received at the first surface or the second surface exits the receiving face at a point.

4. The system of claim **1**, wherein the injected light fans out from the receiving face and deflects from the reflecting face to illuminate the first surface in its entirety.

5. The system of claim **1**, wherein the reflecting face is spherically curved according to a uniform radius of curvature and an angle formed between the first surface and the curved reflecting face is equivalent to an angle formed between the second surface and the curved reflecting face.

6. The system of claim **1**, wherein the first and second surfaces are flat and the thick end is twice as thick as the thin end.

7. The system of claim **1**, wherein the injected light entering the receiving face includes rays that all undergo a same number of reflections from exiting the receiving face to exiting the light guide.

8. The system of claim **1**, wherein the reflecting face is a reflecting grating having layers with refractive indexes that alternate between two index values and thickness that alternates between two thickness values.

9. A lens system, comprising:

a tapered light guide having a display surface and a second guide surface that taper from a thick end to a thin end, the thick end twice in thickness as the thin end;

a receiving face at the thin end for receiving light injected into the light guide; and

a reflecting face at the thick end of the light guide for deflecting incident light back to the display surface, the reflecting face tilted to reduce angles of specular rays relative to a plane of the light guide so that the specular rays exit the display surface before reaching the receiving face.

10. The system of claim **9**, wherein the tilted reflecting face is a Fresnellated surface.

11. The system of claim **9**, wherein the tilted reflecting face is curved about a point distant from the thin end by one light guide length in a direction parallel to an axis of the taper.

12. The system of claim **9**, wherein the reflecting face includes one or more reflecting gratings having layers with refractive indexes that alternate between two index values and thickness that alternates between two thickness values, the one or more reflective grating eliminate aperture diffraction.

13. The system of claim **9**, wherein the reflecting face is spherically curved according to a uniform radius of curvature, and an angle formed between the display surface and the curved reflecting face is equivalent to an angle formed between the second surface and the curved reflecting face.

14. The system of claim **13**, wherein the display surface and the second guide surface each form a right angle to the reflecting face at the thick end.

15. The system of claim **9**, wherein the reflecting face is comprised of three sets of Bragg gratings for illuminating the display surface using red, green and blue colors.

16. The system of claim **9**, wherein the light is injected into a center of the thin end to eliminate a blank margin for fan out.

17. The system of claim **9**, wherein the reflecting face deflects the incident light such that the specular light exits the display surface at a point dependent on an angle of injection of the light.

18. A lens system, comprising:

a wedge-shaped light guide having a display surface and a second guide surface that taper from a thick end to a thin end;

a receiving face at the thin end for receiving light injected into the light guide; and

a reflecting surface at the thick end of the light guide for deflecting incident light back to the display surface, the reflecting surface tilted and curved about a point distant from the thin end of the light guide by one light guide length in a direction parallel to an axis of the taper.

19. The system of claim **18**, wherein the display surface and the second guide surface transition to a section at the thick end where the display surface is parallel to the second guide surface, and the thick end is twice as thick as the thin end.

20. The system of claim **19**, wherein the reflecting surface is a Fresnellated surface having alternating planes of reflective surfaces at correspondingly alternating angles, the planes having normals that share a same component resolved in a plane of the light guide and equal but opposite components perpendicular to the plane of the light guide.

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