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(71) **Applicant: CLEARINK DISPLAY, INC.** [US/US]; 4020 Clipper Court, Fremont, CA 94538 (US).

(72) **Inventor: WHITEHEAD, Lorne, A.**; 2690 Balaclava Street, Vancouver, BC V6K 4E2 (CA).

(74) **Agent: PULLEN, Anthony, E.**; 13058 N Lost Wells Trail, Tucson, AZ 85742 (US).

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(54) **Title:** HIGH BRIGHTNESS RETROREFLECTOR FOR STATIC AND SWITCHABLE IMAGE DISPLAYS

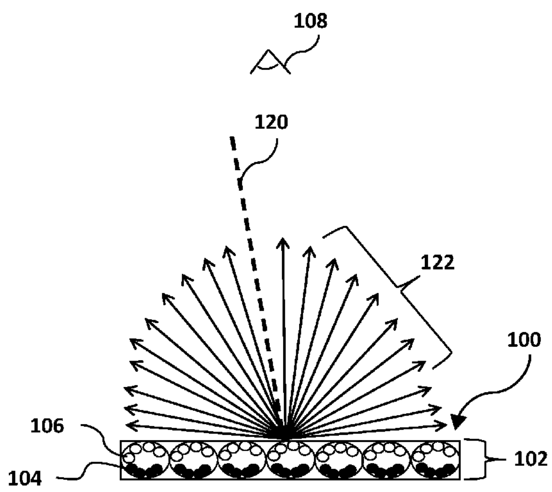

Fig. 1

(57) **Abstract:** Reflective displays typically suffer from low brightness. A novel retroreflector formed of a linear prismatic structure with an array of total internal reflection-based hierarchical microstructures and an opposing specular reflective surface may have potential to replace conventional retroreflectors. Nearly all of the incident light is retroreflected back towards the viewer leading to a brighter display. The novel retroreflectors described herein may be used in static display signage and electronically switchable displays.

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HIGH BRIGHTNESS RETROREFLECTOR FOR STATIC AND SWITCHABLE IMAGE DISPLAYS

The disclosure claims priority to U.S. Provisional Application Serial No. 62/756,186, filed November 6, 2018 (titled "Novel High Brightness Retroreflector for Static and Switchable Image Displays"), the specification of which is incorporated herein in its entirety.

Field

The disclosed embodiments generally relate to reflective image displays. In one embodiment, the disclosure relates to a novel hybrid retroreflector. In another embodiment, the disclosure relates to a hybrid specular/total internal reflection retroreflective display for use in static image displays. In yet another embodiment, the disclosure relates to a hybrid specular/total internal reflection retroreflective display for use in switchable image displays.

BACKGROUND

Conventional retroreflective static traffic display signage is primarily constructed of two basic types of designs. The first conventional design comprises high refractive index glass beads embedded in a film. The beads further have a metallic light reflector coating on the opposite side of the beads. There are health hazards involved in manufacturing and application of the glass beads. For example, the beads contain heavy metals in order to attain high refractive indices. Additional safety measures must be taken for the workers involved. This greatly adds to the cost of manufacture of the beads and the retroreflective film as the result of added manufacturing steps and safety measures.

The second type of conventional retroreflective signage design comprises of micro-replicated corner cube retroreflectors. Corner cube signage comprises corner cube structures with an air gap behind the structures to allow for total internal reflection.

Other signage and display applications use reflective, but not retroreflective, display technology. Conventional microencapsulated electrophoretic displays (*e.g.*, E Ink-based displays) characteristically reflect light in the white state in a so-called Lambertian manner. The reflected light is radiated equally in all directions with equal luminance in the white state. Thus, a large portion of the reflected light is not reflected back to the viewer thereby limiting the perceived brightness of the display.

Fig. 1 schematically illustrates a conventional microencapsulated electrophoretic type display illustrating Lambertian reflectance in the white state. Specifically, Fig. 1 shows display 100 having a layer of microcapsules 102 containing light absorbing black particles 104 and light reflecting particles 106. Display 100 is shown in the white or reflective state where light reflecting particles 106 are located at the outward surface of display 100 towards viewer 108.

An incident light beam depicted by dotted ray 120 is shown where the beam is nearly perpendicular to the outward surface of display 100. The light is reflected in all directions in a Lambertian manner as depicted by the multiple light reflection rays 122. As shown in Fig. 1, a substantial amount of light is not reflected back to the viewer 108. This also prevents the addition of a color filter layer to form a color display due to the limited amount of light that is reflected back towards the viewer. Thus, there is a need to address the shortcomings of conventional reflective switchable image displays.

BRIEF DESCRIPTION OF DRAWINGS

These and other embodiments of the disclosure will be discussed with reference to the following exemplary and non-limiting illustrations, in which like elements are numbered similarly, and where:

Fig. 1 schematically illustrates a conventional microencapsulated electrophoretic type display illustrating Lambertian reflectance in the white state;

Fig. 2A schematically illustrates a novel retroreflector hybridizing specular reflection and total internal reflection;

Fig. 2B schematically illustrates a latitudinal cross-section of novel retroreflector structure 200;

Fig. 2C schematically illustrates an overhead view of novel retroreflector structure 200;

Fig. 2D schematically illustrates a longitudinal cross-section of novel retroreflector structure 200 facing facets 206;

Fig. 2E schematically illustrates a longitudinal cross-section of novel retroreflector structure 200 facing specular reflector surface 208;

Fig. 2F illustrates a close-up view of a portion of retroreflector 200;

Fig. 3 schematically illustrates a cross-section of a portion of a novel retroreflective static display according to one embodiment of the disclosure;

Fig. 4 schematically illustrates a cross-section of a portion of a hybrid TIR-specular reflector switchable image display;

Fig. 5 schematically illustrates an embodiment of a portion of an active matrix thin film transistor array for driving a hybrid TIR-specular reflector-based display; and

Fig. 6 schematically illustrates an exemplary system for implementing an embodiment of the disclosure.

DETAILED DESCRIPTION

Throughout the following description specific details are set forth in order to provide a more thorough understanding to persons skilled in the art. However, well-known elements may not have been shown or described in detail to avoid unnecessarily obscuring the disclosure. Accordingly, the description and drawings are to be regarded in an illustrative, rather than a restrictive sense.

In an exemplary embodiment, a reflective structure comprising at least one light reflective repeat unit wherein the light reflective repeat unit comprises a first facet where incident light is reflected by means of total internal reflection (TIR) when in contact with a medium of lower refractive index, a second facet where incident light ray is reflected by mean of TIR when in contact with a medium of lower refractive index, and a third facet further comprising a reflective coating capable of specular reflection of incident light rays. In one embodiment, the reflective structure comprises a plurality of reflective repeat units wherein the repeat units are arranged in an adjacent manner in a row-like fashion. In another embodiment, the first and second facets where light is reflected by means of TIR are arranged orthogonally with respect to each other. In another embodiment, the first facet and second facets where incident light is reflected by TIR are arranged orthogonally to the third facet capable of specular reflection. In an exemplary embodiment, the third facet comprises a metallized, specularly reflective coating. In some embodiments, the third facet may comprise a partially diffuse reflective coating. In an exemplary embodiment, the light reflective structure comprising one or more light reflective repeat units is further comprised of a material with refractive index greater than about 1.4. In some embodiments, the material may comprise a refractive index in the range of about 1.4-2.4. In an exemplary embodiment, TIR may be frustrated near the surface of the first or second facets using a light absorptive material, such as a plurality of electrophoretic particles suspended in a liquid or air medium or an electrophoretic fluid, that is moved into the evanescent wave region.

In one embodiment, a retroreflector comprises at least one prism wherein the prism comprises a first facet and a second facet. In an exemplary embodiment, one of the facets is further structured with smaller prisms that run in the orthogonal direction. The other facet is coated with a reflective material, such as a metal. In an exemplary embodiment, total internal reflection (TIR) may occur near the surface of the smaller prisms when in contact with a medium of lower refractive index while specular reflection may occur on the metallized facet. The retroreflector may be referred to as a hybrid reflector combining TIR and specular reflection. In an exemplary embodiment, TIR may be frustrated near the surface of the smaller prisms using a light absorptive material, such as a plurality of electrophoretic particles suspended in a liquid or air medium or an electrophoretic fluid, that is moved into the evanescent wave region at the interface of the higher refractive index prisms and lower refractive index medium.

As used herein, a hybrid TIR-specular retroreflective display generally refers to a display that causes reflected light rays within an angular range (roughly +/- 40°) of the incident direction to return predominately back in the incident direction. The retroreflection characteristic is a result of the fact that two facets may reflect light by means of TIR are placed in a substantially orthogonal arrangement with respect to each other, and substantially orthogonal to an opposing third specularly reflective surface. Therefore, the number of reflections that a light ray undergoes before returning to the viewer is three, two by TIR and one reflection by specular reflection. The reflection by TIR can be attenuated by moving an absorbing material or substance into the evanescent wave region near the facets and absorbing light or frustrating TIR. The hybrid geometry causes each reflected light ray to undergo two reflections by TIR and this means that it is possible to get significant attenuation of the reflected light with only a moderate degree of frustration of the reflected light. The hybrid TIR-specular retroreflective display described herein may be used in static image displays and electronically switchable image displays.

Fig. 2A schematically illustrates a novel retroreflector structure hybridizing specular reflection and total internal reflection. Novel retroreflector structure 200 in Fig. 2A comprises sheet 202 with outward surface 204. Sheet 202 may comprise glass. Sheet 202 may comprise a polymer. Sheet 202 may comprise a transparent polymer. In an exemplary embodiment, sheet 202 may comprise polycarbonate, an acrylic or a combination thereof. Sheet 202 may comprise poly(methyl methacrylate) or polyvinyl alcohol (PVA). In some embodiments, sheet 202 may be flexible or conformable (flexible may also be referred to as roll-able or bendable with the ability to be bent without breaking). In some embodiments, sheet 202 may have a thickness in the range of about 1-2000μm. In an exemplary embodiment, sheet 202 may have a thickness in the range of about 20-250μm. Sheet 202 may have a refractive index of about 1.4 or higher. In some embodiments, sheet 202 may include materials having a refractive index in the range of about 1.5-2.4. In other embodiments, sheet 202 may include materials having a refractive index in the range of about 1.5-2.2. In an exemplary embodiment, sheet 202 may have a refractive index of about 1.5-1.9. In certain other embodiments, sheet 202 may be a material having a refractive index in the range of about 1.6-1.9. Sheet 202 may be comprised of a substantially rigid, high index material. High refractive index polymers that may be used may further comprise high refractive index additives such as metal oxides. The metal oxides may comprise one or more of SiO_2, ZrO_2, ZnO_2, ZnO or TiO_2. In one embodiment, sheet 202 may comprise TiO_2 dispersed in PVA. In an exemplary embodiment, sheet 202 may comprise ZrO_2 dispersed in an acrylate-based polymer.

Sheet 202 comprises an outward surface 204. The inward surface of structure 200 in Fig. 2A comprises a first linear prismatic structure 212 comprising facets 206 arranged in a substantially orthogonal manner. A linear prismatic sheet can be characterized in terms of three perpendicular geometrical planes: one plane that is parallel to the sheet itself, a second plane that is perpendicular to the sheet and parallel to the linear prisms, and a third plane that is perpendicular to the sheet and also perpendicular to the linear prisms. Facets 206 and linear prisms 212 may be considered as hierarchical prismatic structures. Structure 200 further comprises an adjacent surface 208 (represented by cross-hatched lines in Figs. 2A-E) that reflects light in a specular manner. The surface of facets 206 may be arranged in a perpendicular manner to surface 208. Surface 208 may comprise a thin specularly reflecting coating. In some embodiments, surface 208 may comprise a thin metallic coating. The thin metallic coating on surface 208 may comprise one or more of aluminum, silver, chromium, nickel, copper or gold. In other embodiments, surface 208 may comprise a multilayer dielectric coating capable of specular reflection. In some embodiments, surface 208 may comprise a partially diffuse reflective coating. The partially diffuse reflective coating may comprise TiO_2, Teflon or other material.

Fig. 2B schematically illustrates a latitudinal cross-section of novel retroreflector structure 200. Cross-section view in Fig. 2B shows outward surface 204 facing viewer 210. The opposite or inward surface comprises prismatic structures 212. A single prismatic structure 212 comprises a pair of facets 206 arranged substantially perpendicular to each other and additionally substantially perpendicular to opposing adjacent specular reflective surface 208. In some embodiments, the width of facets 206 (denoted w_f) of the linear prismatic structure, is less than, (preferably less than about half, and more preferably less than about one-fourth) the width (denoted w_{sf}) of the smallest dimension of the specular reflective surface 208. In other embodiments, the width of facets 206 of the linear prismatic structure, is less than about half the width of the smallest dimension of the specular reflective surface 208. In an exemplary embodiment, the width of each facet 206 of the linear prismatic structure, is less than about one-fourth the width of the smallest dimension of the specular reflective surface 208.

Prismatic structures 212 may be arranged in rows 214. The distance or spacing between the rows of prismatic structures 212 may be represented by pitch 216 (denoted by p in Fig. 2B), wherein the pitch is the distance between where surfaces 206 and 208 meet. Row pitch 216 may be in a substantially regular or random array. In some embodiments, pitch 216 may range from about 0.1 micrometers to about 5000 micrometers. In other embodiments, pitch 216 may be in the range of about 1 micrometer to about 3000 micrometers. In still other embodiments, pitch 216 may be in the range of about 10 micrometers to about 1000 micrometers.

In some embodiments, the angle α formed between the surface of facets 206 and specular reflector surface 208 may be in the range of about 75° to about 105°. In other embodiments, angle α may be in the range of about 85° to about 95°. In an exemplary embodiment, angle α may be about 90° wherein facets 206 are substantially orthogonal to facet 208. In some embodiments, the angle β formed between the surface of facets 206 and specular reflector surface 208 and facing outer surface 204 may be in the range of about 75° to about 105°. In other embodiments, angle β may be in the range of about 85° to about 95°. In an exemplary embodiment, angle β may be about 90° wherein facets 206 are substantially orthogonal to facet 208.

Retroreflector 200 illustrated in Fig. 2B may also be described as comprising one or more prisms 212 wherein the prisms comprise a first facet 211 further comprising smaller prisms with facets 206. Prism 212 comprises a second facet 213 that is arranged orthogonal to the smaller prisms of the first facet 206 and further comprises a light reflecting coating 208. The first facet 211 may be comprised of a transparent material having a first refractive index and reflects incident light by means of total internal reflection when in contact with a medium at the surface of prisms 206 with a lower second refractive index. The light reflecting coating 208 on second facet 213 may comprise a metal such as one or more of aluminum, silver, nickel, chromium, copper or gold.

Fig. 2C schematically illustrates an overhead view of novel retroreflector structure 200. The overhead view illustrates how facets 206 are perpendicular to each other and may be arranged in pairs 218. Pairs 218 of facets 206 are further arranged in rows 220. Rows 220 of facets 206 are separated by specular reflector surfaces 208. Rows 220 of facets 206 that are aligned in a substantially orthogonal direction to specular reflector surface 208 may form rows 214 of prismatic structures 212 (denoted in Fig. 2B).

Fig. 2D schematically illustrates a longitudinal cross-section of novel retroreflector structure 200 facing facets 206. In this view, the longitudinal cross-section is made between rows 220 of facets 206 and specular reflector layer 208 wherein exposing a direct view of the rows 220 of facets 206. This view further illustrates how facets 206 may be arranged in pairs 218. The angle between pairs of facets 206 is represented by angle γ. In some embodiments, angle γ may be in the range of about 75° to about 105°. In other embodiments, angle γ may be in the range of about 85° to about 95°. In an exemplary embodiment, angle γ is about 90°.

Fig. 2E schematically illustrates a longitudinal cross-section of novel retroreflector structure 200 facing specular reflector coating surface 208. In this view, the longitudinal cross-section is made between rows 220 of facets 206 and specular reflector layer 208 wherein exposing a direct view of the specular reflector surface 208.

Fig. 2F illustrates a close-up view of a portion of retroreflector 200. The portion of retroreflector 200 may be also referred to as a light reflecting repeat unit 222. Retroreflector may comprise one or more light reflecting repeat units 222. Repeat unit 222 comprises a first and second facet 206 of substantially the same dimensions that are arranged at angle γ that is substantially orthogonal with respect to each other. Repeat unit 222 further includes a third facet that further comprises a light reflecting coating 208 and is substantially orthogonal to the first and second facets 206 (denoted by angle α). In some embodiments, angle α may be in the range of about 75° to about 105°. In other embodiments, angle α may be in the range of about 85° to about 95°. In an exemplary embodiment, angle α is about 90°. The first and second facets 206 may be comprised of a transparent material having a first refractive index and reflects incident light by means of total internal reflection (TIR) at the surface when in contact with a medium with a lower second refractive index.

Fig. 2F illustrates typical reflection modes at the surface of facets 206 and light reflecting coating 208. The following is an example mode of retroreflection in hybrid retroreflector embodiment 200. Other reflection modes may be possible. Incident light ray 240, represented by a dotted line, enters structure 212 where the light is reflected by TIR off a first facet 206 at location 242. The light ray is reflected towards a second facet 206 at location 244 where it again undergoes TIR at the interface between the surface of a high index of refraction material that makes up retroreflector 200 with a lower index of refraction medium (*e.g.*, air). The light ray may then be reflected towards specular reflection layer 208 wherein the light ray is specularly reflected at location 246 as reflected light ray 248 towards viewer 210 in the direction from which incident light ray 240 originated from. The reflection mode described illustrates the ability of optical structure 200 to hybridize total internal reflection and specular reflection. Structure 200 combines a first prismatic linear structure comprising two orthogonal surfaces 206 that reflects light by total internal reflection with an adjacent surface 208 that reflects light in a specular manner and is further aligned in an orthogonal manner to facets 206. The geometrical relationship between the three surfaces is selected to ensure that after the last reflection the ray is traveling in the direction opposite to its incoming direction. The geometrical relationship leads to one of three reflection modes wherein light is retroreflected after three reflections comprising of two TIR reflections and one specular reflection: facet-facet-specular layer (illustrated in Fig. 2F), facet-specular layer-facet or specular layer-facet-facet. Furthermore, the selection of the sizes and orientations of the three surfaces enables a significant fraction of light rays incident within a preferred range of near-normal directions to undergo retroreflection. The normal vectors of the surfaces of the linear prisms are substantially orthogonal to one another and are inclined at more than 55° from the normal vector of the overall plane of incidence of the system. The retroreflector design 200 described herein virtually retroreflects all incident light within the useful viewing range of about +/-40°.

A variety of current microfabrication techniques may be used to create the novel retroreflector designs described herein. Such microfabrication techniques comprise one or more of photolithography, shadow masking, chemical vapor deposition (CVD), physical vapor deposition (PVD), plasma etching, reactive-ion etching (RIE), wet etching, polishing, electroplating, microforming, microextrusion, microstamping, microcutting and chemical-mechanical planarization (CMP).

Fig. 3 schematically illustrates a cross-section of a portion of a novel retroreflective static display according to one embodiment of the disclosure. Retroreflective display embodiment 300 in Fig. 3 comprises a hybrid retroreflector as described in Figs. 2A-E. Display 300 comprises a transparent sheet 302 with outward surface 304 facing viewer 306. Sheet 302 comprises facets 308 and specular reflector layer 310 to form prismatic structures as previously described. The prismatic structures are arranged in arrays 312 of rows and columns. In an exemplary embodiment, sheet 302 may comprise a flexible glass or polymer. In an exemplary embodiment, sheet 302 may comprise glass or polymer or a combination thereof of thickness in the range of about 20-500 microns. Sheet 302 may comprise a polymer such as polycarbonate or poly(methyl methacrylate) or other acrylic polymer. In an exemplary embodiment, sheet 302 may comprise a transparent polymer. In some embodiments, sheet 302 may be flexible or conformable (flexible may also be referred to as rollable or bendable with the ability to be bent without breaking). In some embodiments, sheet 302 may have a thickness in the range of about 1-2000μm. In an exemplary embodiment, sheet 302 may have a thickness in the range of about 20-250μm. Sheet 302 may have a refractive index of about 1.4 or higher. In an exemplary embodiment, sheet 302 may have a refractive index of about 1.5-1.9. In certain embodiments, sheet 302 may include materials having a refractive index in the range of about 1.5-2.4. In certain other embodiments sheet 302 may be a material having a refractive index of about 1.6-1.9. Sheet 302 may be comprised of a substantially rigid, high index material. High refractive index polymers that may be used may further comprise high refractive index additives such as metal oxides. The metal oxides may comprise one or more of SiO_2, ZrO_2, ZnO_2, ZnO or TiO_2.

Retroreflective display 300 may further comprise a rear support sheet 314. Rear sheet 314 may be one or more of a metal, polymer, wood or other material. Sheet 314 may be one or more of glass, polycarbonate, polymethylmethacrylate (PMMA), polyurethane, acrylic, polyvinylchloride (PVC) or polyethylene terephthalate (PET). Sheet 314 may be rigid or flexible.

Retroreflective display embodiment 300 may further comprise a light reflective layer 316 located on rear support sheet 314. Layer 316 may comprise a metal such as aluminum, chromium, nickel, copper, gold or silver. Light reflective layer 316 may be formed by sputtering, vacuum deposition or other method. Light reflective layer 316 may be continuous or patterned. Light reflective layer 316 may be a diffuse reflector and may comprise one or more of TiO_2 or Teflon™.

Retroreflective display embodiment 300 may further comprise spacers 318. The spacers may maintain a substantially uniform spacing distance or gap 320 between sheet 302 and the layer 314. Spacer structures may be used to support the various layers in the displays. The spacer structures may be in the shape of circular or oval beads, blocks, cylinders, walls or other geometrical shapes or combinations thereof. Spacer structures 318 may comprise glass, metal or polymer. Gap 320 may be filled with a liquid or gaseous medium 322. In an exemplary embodiment, medium 322 may comprise ambient air or a gas such as argon or N_2. In an exemplary embodiment, medium 322 in gap 320 may have a refractive index lower than the refractive index of sheet 302. Medium 322 may have a refractive index in the range of about 1-1.5. In an exemplary embodiment, the ratio of the refractive index of sheet 302 to the refractive index of medium 322 may be in the range of about 1.05 to about 2.20.

Retroreflective display embodiment 300 may further comprise an adhesive layer 324. Adhesive layer 324 may be located behind rear support sheet 314. In other embodiments, adhesive layer 324 may be interposed between light reflective layer 316 and rear support 314 such that rear support layer 314 may also act as a release sheet to expose adhesive layer 324.

Adhesive layer 324 may comprise a polymer. Adhesive 324 may comprise one or more of a solvent-based adhesive, emulsion adhesive, polymer dispersion adhesive, pressure-sensitive adhesive, contact adhesive, hot-melt adhesive, multi-component adhesive, ultra-violet (UV) light curing adhesive, heat curing adhesive, moisture curing adhesive, natural adhesive or any other synthetic adhesive.

Retroreflective display 300 may further comprise release sheet 326. Release sheet 326 may be comprised of a material such that it may be readily removed so that the multi-layered structure 300 may be laminated or adhered to any structure or location where a static semi-retroreflective display is desired. Display 300 may be placed on a traffic sign, wall, roadway, clothing, bicycle, motorized vehicle or other application where it may be desired to have a reflective display. Release sheet 326 may comprise polymer or paper.

Retroreflective display 300 may further comprise a transparent image layer 328. Layer 328 may be continuous or patterned to convey information to a viewer such as one or more of a picture, letters, number, words, phrases or signage. Layer 328 may comprise one or more colors. Image layer 328 may comprise at least one dye. Image layer 328 may impart at least one color to the display. Layer 328 may be adhered to display 300 by an optically clear adhesive (not shown) located between layer 328 and sheet 302.

Retroreflective display 300 may further comprise an optional transparent outer layer or coating 330. Layer 330 may be a protective layer. Layer 330 may protect the display from physical damage or UV-light damage. Protective layer 330 may also comprise at least one color in a continuous or patterned manner. Layer 330 may comprise a polymer or glass.

Display embodiment 300 may reflect light and display an image as follows. Incident light, represented by light ray 340 in Fig. 3, may pass through layers 328, 330 and sheet 302. Light ray 340 may undergo TIR at the interface of higher refractive index of refraction facet 308 and lower index of refraction medium 322 if the angle of the light to the interface is larger than the critical angle, θ_c. A small critical angle (*e.g.*, less than about 50°) is preferred at facets 308 since this affords a large range of angles over which TIR may occur. It may be prudent to have air located in gap 320 with preferably as small a refractive index (η_3) as possible and to have facets 308 comprising a material having a refractive index (η_1) preferably as large as possible. The critical angle, θ_c, is calculated by the following equation (Eq. 1):

$$\theta_c = \sin^{-1}\left(\frac{\eta_3}{\eta_1}\right) \qquad (1)$$

In a first example mode of reflection, light ray 340 may be reflected at facets 308 by means of total internal reflection towards specular reflector surface 310 where the light ray may then be reflected back towards viewer 306 as substantially retroreflected light ray 342. In a second example mode of light reflection, incident light ray 344 may pass through layers 328, 330 and sheet 302 towards specular reflection layer 310. Light ray 344 may then be specularly reflected towards the interface of the higher refractive index facets 308 and lower refractive index medium 322. At this location, total internal reflection may occur at first and second facets 308 where light ray 344 is reflected as light ray 346 towards viewer 306. In both example modes of reflection, the light may be reflected off of a first and second facet and the specular reflective layer such that three reflections occur each time light is retroreflected in display 300. The reflected light from static display 300 enhances the display image to viewer 306 by image layer 328.

In some instances, based on the application of static display 300, it may be important to have a whiter, more diffuse appearance. Display 300 may comprise a light diffuser layer. A diffuser layer may be used to soften the incoming light or reflected light or to reduce glare. Diffuser layer may comprise a flexible polymer. Diffuser layer may comprise ground glass in a flexible polymer matrix. Diffuser may comprise a micro-structured or textured polymer. Diffuser layer may comprise 3M™ anti-sparkle or anti-glare film. Diffuser layer may comprise 3M™ GLR320 film (Maplewood, MN) or AGF6200 film. A diffuser layer may be located at one or more various locations within the display embodiments described herein. In one embodiment, the diffuser layer may be located on top or below image layer 328.

Another method to create a whiter, more diffuse appearance for static display 300 is to add additives to sheet 302. Additives of sizes larger than the wavelength of light may be added to scatter the incident light. The magnitude of the scatter may be controlled by the size and type of additives. For example, TiO_2 may be added and dispersed in sheet 302. The TiO_2 may be of an optimal size range to not prevent light from passing through sheet 302 but scatter enough light to create a more visually appealing, whiter display.

Fig. 4 schematically illustrates a cross-section of a portion of a hybrid TIR-specular reflector switchable image display. Display 400 in Fig. 4 comprises a transparent sheet 402 further comprising an inward array 406 of hybrid prismatic linear structures 404 comprising facets 408 and an opposing specular reflector surface 410 as previously illustrated in Figs. 2A-F and described herein. In some embodiments, sheet 402 and hybrid retroreflectors 404 may be a continuous sheet of the same material. In other embodiments, sheet 402 and hybrid retroreflectors 404 may be separate layers and comprised of different materials. In an exemplary embodiment, sheet 402 and hybrid retroreflectors 404 may comprise substantially the same refractive index or different refractive indices. In an exemplary embodiment, sheet 402 may comprise a flexible glass. In an exemplary embodiment, sheet 402 may comprise glass of thickness in the range of about 20-250 microns. Sheet 402 may comprise a flexible glass such as SCHOTT AF 32® eco or D 263® T eco ultra-thin glass. Sheet 402 may comprise a transparent polymer such as polycarbonate, poly(methyl methacrylate) or other acrylic-based polymer. In an exemplary embodiment, sheet 402 may comprise a flexible polymer.

Sheet 402 comprises facets 408 and specular reflector layer 410 to form prismatic structures 404 as previously described. Prismatic structures 404 may be arranged in arrays 406 of rows and columns. In an exemplary embodiment, sheet 402 may comprise a flexible glass or polymer. In an exemplary embodiment, sheet 402 may comprise glass or polymer or a combination thereof of thickness in the range of about 20-500 micrometers. In an exemplary embodiment, sheet 402 may comprise a transparent polymer. In some embodiments, sheet 402 may be flexible or conformable (flexible may also be referred to as rollable or bendable with the ability to be bent without breaking). In some embodiments, sheet 402 may have a thickness in the range of about 1-2000μm. In an exemplary embodiment, sheet 402 may have a thickness in the range of about 20-250μm. Sheet 402 and structures 404 may have a refractive index of about 1.4 or higher. In an exemplary embodiment, sheet 402 may have a refractive index of about 1.5-1.9. In certain embodiments, sheet 402 may include materials having a refractive index in the range of about 1.5-2.4. In some embodiments, sheet 402 may include materials having a refractive index in the range of about 1.5-2.2. In certain other embodiments sheet 402 may be a material having a refractive index of about 1.6-1.9. Sheet 402 may be comprised of a substantially rigid, high index material. High refractive index polymers that may be used may further comprise high refractive index additives such as metal oxides. The metal oxides may comprise one or more of SiO_2, ZrO_2, ZnO_2, ZnO or TiO_2.

Display embodiment 400 in Fig. 4 may comprise a color filter array layer 412. Color filter array layer 412 may be located on the outward surface of sheet 402 facing viewer 414. In an exemplary embodiment, color filter array layer 412 may be located between sheet 402 and hybrid retroreflector array layer 406. Color filter layer 412 may comprise one or more of red (R), green (G), blue (B), white (W), clear, black, cyan, magenta or yellow sub-pixel filters. In an exemplary embodiment, color filter layer 412 may be one or more of rigid, flexible or conformable.

In an exemplary embodiment, each hybrid retroreflector 404 may be substantially aligned with a single color sub-filter. In an exemplary embodiment, color filter array layer 412 may comprise a PenTile™ array of sub-pixel color filters. Color filter array layer 412 may comprise one or both of PenTile™ RGBG array of sub-pixel filters or PenTile™ RGBW array of sub-pixel filters. The color sub-filter may be arranged such that an exemplary pixel may comprise, for example, three different sub-filters (*e.g.*, red, green and blue). Thus, depending on the application, the pixel may reflect one of red, green or blue colors.

Display embodiment 400 in Fig. 4 may include at least one barrier layer 414. Barrier layer 414 may be transparent. Barrier layer 414 may be one or more of rigid, flexible and conformable. Barrier layer 414 may be located in various locations within the hybrid retroreflector-based display embodiment described herein. Barrier layer 414 may act as one or more of a gas barrier or moisture barrier and may be hydrolytically stable. Barrier layer 414 may be one or more of a flexible or conformable polymer. Barrier layer 414 may comprise one or more of polyester, polypropylene, polyethylene terephthalate, polyethylene naphthalate or copolymer, or polyethylene. Barrier layer 414 may comprise glass. Barrier layer 414 may comprise one or more of a chemical vapor deposited (CVD) or sputter coated ceramic-based thin film on a polymer substrate. The ceramic may comprise one or more of Al_2O_3, SiO_2 or other metal oxide. Barrier layer 414 may comprise one or more of a Vitriflex barrier film, Invista OXYCLEAR® barrier resin, Toppan GL™ barrier films GL-AEC-F, GX-P-F, GL-AR-DF, GL-ARH, GL-RD, Celplast Ceramis® CPT-036, CPT-001, CPT-022, CPA-001, CPA-002, CPP-004, CPP-005 silicon oxide (SiO_x) barrier films, Celplast CAMCLEAR® aluminum oxide (AlOx) coated clear barrier films, Celplast CAMSHIELD® T AlOx-polyester film, Torayfan® CBH or Torayfan® CBLH biaxially-oriented clear barrier polypropylene films.

Display embodiment 400 in Fig. 4 may comprise a diffuser layer 416. Diffuser layer 416 may be used to soften the incoming light or reflected light or to reduce glare. Diffuser layer 416 may comprise a flexible polymer or glass. Diffuser layer 416 may be one or more of rigid, flexible and conformable. Diffuser layer 416 may comprise ground glass in a flexible polymer matrix. Layer 416 may comprise a micro-structured or textured polymer. Diffuser layer 416 may comprise 3M™ anti-sparkle or anti-glare film. Diffuser layer 416 may comprise 3M™ GLR320 film (Maplewood, MN) or AGF6200 film. Diffuser layer 416 may be located at one or more various locations within display embodiment 400 in Fig. 4.

Display embodiment 400 in Fig. 4 may include at least one optically clear adhesive (OCA) layer 418. OCA layer 418 may be one or more of rigid, flexible or conformable. OCA's may be used to adhere display layers together and to optically couple layers. TIR-based display embodiment 400 in Fig. 4 may comprise optically clear adhesive layers further comprised of one or more of 3M™ optically clear adhesives 3M™ 8211, 3M™ 8212, 3M™ 8213, 3M™ 8214, 3M™ 8215, 3M™ OCA 8146-X, 3M™ OCA 817X, 3M™ OCA 821X, 3M™ OCA 9483, 3M™ OCA 826XN or 3M™ OCA 8148-X, 3M™ CEF05XX, 3M™ CEF06XXN, 3M™

CEF19XX, 3M™ CEF28XX, 3M™ CEF29XX, 3M™ CEF30XX, 3M™ CEF31, 3M™ CEF71XX, Lintec MO-T020RW, Lintec MO-3015UV series, Lintec MO-T015, Lintec MO-3014UV2+, Lintec MO-3015UV.

Display 400 in Fig. 4 may comprise a front light system 420 with outer surface 422 facing viewer 414. Front light system 420 may comprise a light source 424 to emit light through an edge of a light guide 426. Light source 424 may comprise one or more of a light emitting diode (LED), cold cathode fluorescent lamp (CCFL) or a surface mounted technology (SMT) incandescent lamp. In an exemplary embodiment, light source 424 may define an LED whose output light emanates from a refractive or reflective optical element that concentrates said diode's output emission in a condensed angular range to an edge of light guide 426. In an exemplary embodiment, front light system 420 may comprise an angle transformer (not shown). In some embodiments, light source 424 may be optically coupled to light guide 426. Front light system 420 may be flexible or rigid.

Light guide 426 may comprise one or more of a rigid, flexible or conformable polymer. Light guide 426 may comprise more than one layer. Light guide 426 may comprise one or more contiguous light guiding sub-layers parallel to each other. Light guide 426 may comprise at least a first light guiding sub-layer (not shown) that forms a transparent bottom surface. Light guide 426 may comprise a second sub-layer that forms a transparent top or outer surface. Light guide 426 may comprise a third sub-layer that forms a central transparent core. The refractive indices of the sub-layers of light guide 426 may differ by at least 0.05. The multiple sub-layers may be optically coupled.

In an exemplary embodiment, light guide 426 may comprise an array of light extractor elements (not shown). The light extractor elements may be one or more of rigid, flexible or conformable. The light extractor elements may comprise one or more of light scattering particles, dispersed polymer particles, tilted prismatic facets, parallel prism grooves, curvilinear prism grooves, curved cylindrical surfaces, conical indentations, spherical indentations, aspherical indentations or air pockets. The light extractor elements may be arranged such that they redirect light towards sheet 402 in a substantially perpendicular direction with a non-Lambertian narrow-angle distribution. In other embodiments, the light extractor elements may be arranged such that they re-direct light in a slightly off-axis angle towards sheet 402 such that Fresnel and other unwanted reflections are reflected away from the viewer. Light guide 426 may comprise diffusive optical haze. The light guide system in display embodiment 400 may comprise a FLEx Front Light Panel made from FLEx Lighting (Chicago, IL). Light guide 426 may comprise an ultra-thin, flexible light guide film manufactured by Nanocomp Oy, Ltd. (Lehmo, Finland).

Sheet 402 may further comprise a front electrode layer 428 located on the surface of the facets 408 or on facets 408 and specular reflector layer 410. Front electrode layer 428 may be one or more of rigid, flexible or conformable. Front electrode layer 428 may comprise a transparent conductive material such as indium tin oxide (ITO), Baytron™, or conductive nanoparticles, silver wires, metal nanowires, graphene, nanotubes, or other conductive carbon allotropes or a combination of these materials dispersed in a substantially transparent polymer. Front electrode layer 428 may comprise a transparent conductive material further comprising silver nanometer sized wires manufactured by C3Nano (Hayward, CA, USA). Front electrode layer 428 may comprise C3Nano ActiveGrid™ conductive ink.

Display embodiment 400 in Fig. 4 may further comprise a rigid, flexible or conformal rear support layer 430. Rear support layer 430 may be one or more of a metal, polymer, wood or other material. Sheet 430 may one or more of glass, polycarbonate, polymethylmethacrylate (PMMA), polyurethane, acrylic, polyvinylchloride (PVC), polyimide or polyethylene terephthalate (PET).

In an exemplary embodiment, a rear electrode layer 432 may be located on the inner surface of rear support layer 430. Rear electrode layer 432 may be rigid, flexible or conformal. Layer 432 may comprise transparent conductive material or non-transparent conductive material such as aluminum, silver, gold or copper. Rear electrode layer 432 may be vapor deposited or electroplated. Rear electrode 432 may be continuous or patterned. Rear electrode 432 may be integrated with rear support layer 430. Alternatively, rear electrode 432 may be positioned proximal to rear support 430. In another embodiment, rear electrode 432 may be laminated or attached to rear support layer 430. Rear support 430 may form a gap or cavity 434 therebetween with the array layer of hybrid retroreflectors 406. Rear electrode layer 432 may comprise a thin film transistor (TFT) array or a passive matrix array. Rear electrode layer 432 may comprise a direct drive patterned array of electrodes or a segmented array of electrodes. Rear electrode layer 432 may comprise an active matrix of organic field-effect transistors (FETs). The organic FETs may comprise an active semiconducting layer of a conjugated polymer or a small conjugated molecule. The organic FETs may comprise an organic dielectric layer in the form of either a solution processed dielectric or a chemical vapor deposited dielectric. Layer 432 may comprise aluminum, ITO, silver, copper, gold or other electrically conductive material. In one embodiment, layer 432 may comprise organic TFTs. In other embodiments, rear electrode layer 432 may comprise indium gallium zinc oxide (IGZO) TFTs. Layer 432 may comprise low temperature polysilicon, low temperature polysilicon manufactured by a polyimide "lift-off" process, amorphous silicon on a flexible substrate or TFTs on flexible substrates manufactured by FlexEnable (Cambridge, United Kingdom) or those manufactured by FlexEnable and Merck (Darmstadt, Germany). In an exemplary embodiment, each TFT of rear electrode layer 432 may be substantially aligned or registered with at least one sub-pixel filter in color filter array layer 412.

In an exemplary embodiment, layer 432 may comprise a planarization layer (not shown). A planarization layer may be used to smooth the surface of the backplane drive electronics. The planarization layer may allow complete sidewalls or partial sidewalls to be placed or formed on top of the planarization layer. The planarization layer may be flexible and/or conformable. The planarization layer may comprise a polymer. The planarization layer may be deposited using a slot die coating process or flexo-print process. The planarization layer may comprise a photoresist. The planarization layer may also act as a dielectric layer. The planarization layer may comprise a polyimide.

In some embodiments, display 400 may be bent such that the display may be forced into a convex or concave shape or any other shape desirable relative to viewer 414. In some embodiments, display 400 may be flexed in more than one direction, such as in the form of an S-curve.

Display 400 may be also bendable, rollable, wrappable, foldable, twistable or impact resistant. Flexible display 400 may be flexible in nature such that the display may substantially retain optimal optical properties and performance in a bent or flexed state as in a non-flexed or non-bent state. In an exemplary embodiment, display 400 may retain its original shape after the force causing the bending (or contortion) is removed. In still another embodiment, display 400 may stay in the deformed state even after the force causing the bending (or contortion) is removed. Display 400 may be bent or flexed as for applications such as roll-able displays or foldable displays for electronic newspapers and electronic signage. Display 400 may be placed on curved or contoured surfaces, such as dashboards, appliances or even the skin of a human or animal for medical diagnostic or other purposes.

Sidewalls 436 or spacer units (not shown) may be implemented to aid in maintaining a substantially uniform distance between front electrode 428 and rear electrode 432 when display embodiment 400 is in a non-flexed or flexed state. Sidewalls may also be referred to as cross-walls, pixel walls or partition walls. Sidewalls 436 may limit particle settling, drift and diffusion to improve display performance and bistability. In an exemplary embodiment, sidewalls may substantially maintain a uniform gap distance between the front electrode 428 and rear electrode

432 when the display is flexed or bent. Sidewalls 436 may also act as a barrier to aid in preventing prevent moisture and oxygen ingress into the display. Sidewalls 436 may be located within the light modulation layer comprising particles 440 and medium 438.

Sidewalls 436 may completely or partially extend from the front electrode, rear electrode or both the front and rear electrodes. Sidewalls 436 may comprise polymer, metal or glass or a combination thereof. Sidewalls 436 may be any size or shape. Sidewalls 436 may have a rounded cross-section.

Sidewalls 436 may have a refractive index within about 0.01-0.2 of the refractive index of hybrid retroreflector structures 404. In an exemplary embodiment, sidewalls 436 may be optically active. Sidewalls 436 may create wells or compartments to confine electrophoretically mobile particles 440 suspended in medium 438. Sidewalls 436 may be configured to create wells or compartments in, for example, square-like, triangular, pentagonal or hexagonal shapes or a combination thereof.

Sidewalls 436 may comprise a polymeric material and patterned by one or more conventional techniques including photolithography, embossing or molding. In certain embodiments, display 400 comprises sidewalls 436 that completely bridge gap 434. In other embodiments, display embodiment 400 may comprise partial sidewalls that only partially bridge gap 434. In certain embodiments, reflective image display 400 may comprise a combination of sidewalls and partial sidewalls that may completely or partially bridge gap 434. In an exemplary embodiment, sidewalls 434 may be comprised of a rigid, flexible or conformal polymer. In other embodiments, sidewalls 434 may be substantially aligned with color filter sub-pixels of color filter layer 412.

In some embodiments, sidewalls 436 may be formed on top of rear dielectric layer 444, rear electrode layer 432 or rear substrate 430. In the example in Fig. 4, sidewalls 436 are formed directly on rear dielectric later 444. In other embodiments, sidewalls may be formed as part of the array 406 of hybrid retroreflector structures. Dielectric layer 448 may also be located on sidewalls 436. Sidewalls 436 may be formed on top of a planarization layer.

In an exemplary embodiment, hybrid TIR-specular reflector-based display 400 may be driven by backplane electronics comprising an active matrix thin film transistor array typically used in liquid crystal displays (LCDs). Fig. 5 schematically illustrates an embodiment of a portion of an active matrix thin film transistor array for driving a hybrid TIR-specular reflector-based display. Backplane electronics embodiment 500 is comprised of an array of pixels 502 that may be used to drive a flexible TIR-based display. A single pixel 502 is highlighted by a dotted line box in Fig. 5. Pixels 502 may be arranged in rows 504 and columns 506 as illustrated in Fig. 5 but other arrangements may be possible. In an exemplary embodiment, each pixel 502 may comprise a single TFT 508. In array embodiment 500, each TFT 508 is located in the upper left of each pixel 502. In other embodiments, the TFT 508 may be placed in other locations within each pixel 502. Each pixel 502 may further comprise a conductive layer 510 to address each pixel of the display. Layer 510 may comprise ITO, aluminum, silver, copper, gold, Baytron™, or conductive nanoparticles, silver wires, metal nanowires, graphene, nanotubes, or other conductive carbon allotropes or a combination of these materials dispersed in a polymer. Backplane electronics embodiment 500 may further comprise column 512 and row 514 wires. Column wires 512 and row wires 514 may comprise a metal such as aluminum, silver, copper, gold or other electrically conductive metal. Column 512 and row 514 wires may comprise ITO. The column 512 and row 514 wires may be attached to TFTs 508. Pixels 502 may be addressed in rows and columns. TFTs 508 may be formed using amorphous silicon or polycrystalline silicon. The silicon layer for TFTs 508 may be deposited using plasma-enhanced chemical vapor deposition (PECVD). In an exemplary embodiment, each pixel may be substantially aligned with a single color filter in layer 412. Column wires 512 and row wires 514 may be further connected to integrated circuits and drive electronics to drive the display.

Display embodiment 400 may further comprise a low refractive index medium 438 located between front electrode 428 and rear electrode 432 in gap 434. Medium 438 may be air or a liquid. Medium 438 may be an inert, low refractive index fluid medium. Medium 438 may be a hydrocarbon. In some embodiments the refractive index of medium 438 may be in the range of about 1-1.5. In still other embodiments, the refractive index of medium 438 may be in the range of about 1.1-1.4. In an exemplary embodiment, medium 438 may be a fluorinated hydrocarbon. In another exemplary embodiment, medium 438 may be a perfluorinated hydrocarbon. In an exemplary embodiment, medium 438 has a refractive index less than the refractive index of sheet 402 or hybrid retroreflectors 404. In other embodiments, medium 438 may be a mixture of a hydrocarbon and a fluorinated hydrocarbon. In an exemplary embodiment, medium 438 may comprise one or more of Fluorinert™, Novec™ 7000, Novec™ 7100, Novec™ 7300, Novec™ 7500, Novec™ 7700, Novec™ 8200, electrowetting materials, Teflon™ AF, CYTOP™ or Fluoropel™.

Medium 438 may further comprise one or more of a viscosity modifier or a charge control agent. Conventional viscosity modifiers include oligomers or polymers. Viscosity modifiers may include one or more of a styrene, acrylate, methacrylate or other olefin-based polymers. In one embodiment, the viscosity modifier is polyisobutylene. In another embodiment, the viscosity modifier is a halogenated polyisobutylene.

Medium 438 may further receive a plurality of light absorbing electrophoretically mobile particles 440. Mobile particles 440 may comprise a first charge polarity and first optical characteristic (*i.e.* color or light absorption characteristic). In some embodiments, medium 438 may further include a second plurality of electrophoretically mobile particles further comprising a second charge of opposite polarity and a second optical characteristic. Particles 440 may be formed of an organic material or an inorganic material or a combination of an organic and inorganic material. The particles may have a polymer coating. Particles 440 may comprise a coating of an organic material or an inorganic material or a combination of an organic and inorganic material. Particles 440 may be a dye or a pigment or a combination thereof. Particles 440 may be at least one of carbon black, a metal or metal oxide. In an exemplary embodiment, particles 440 may comprise $CuCrO_4$. In one embodiment, particles 440 illustrated in embodiment 400 in Fig. 4 may consist of a positive charge polarity or a negative charge polarity or a combination thereof. Particles 440 may comprise weakly charged or uncharged particles. Particles 440 may be light absorbing or light reflecting or a combination thereof. Particles 440 may also have light absorption characteristics such that they may impart any color of the visible spectrum or a combination of colors to give a specific shade or hue.

In another embodiment, display embodiment 400 may comprise a plurality of light absorbing particles 440 and a second plurality of light reflecting particles. The light reflective particles may comprise a white reflective particle such as titanium dioxide (TiO_2). The light reflective particles may be around 200-300nm. This is a typical size of TiO_2 particles used in the paint industry to maximize light reflectance properties. Particles of larger or smaller sizes may also be used. The light reflective particles may further comprise a coating (not shown). The coating on the light reflecting materials may comprise an organic material or an inorganic material such as a metal oxide. The coating may comprise of an effective refractive index that is substantially similar to the refractive index of medium 438. In some embodiments, the difference between the refractive indices of the coating on the light reflecting particles and medium 438 may be about 40% or less. In other embodiments, the difference between the refractive indices of the coating on the light reflecting particles and medium 438 may be about 0.5-40%.

In other embodiments, medium 438 may also comprise an electrowetting fluid. In an exemplary embodiment, the electrowetting fluid may comprise a dye. The electrowetting fluid may move towards hybrid retroreflectors 404 into the evanescent wave region to frustrate TIR. The electrowetting fluid may move away from hybrid retroreflectors 404 and out of the evanescent wave region to allow for TIR. The electrowetting fluid may be a silicone oil that may be pumped via small channels into and out of the wells formed by sidewalls.

Display 400 may further include an optional dielectric layer 442 positioned on the surface of transparent front electrode 428 and interposed between transparent front electrode 428 and medium 438. Display 400 may further include an optional rear dielectric layer 444 positioned on the surface of rear electrode 432 and interposed between rear electrode 432 and medium 438. The rear dielectric layer may be flexible and/or conformable. The one or more optional dielectric layers may be used to protect one or both of front electrode layer 428 or rear electrode layer 432. In some embodiments, dielectric layer 442 on front electrode 428 may comprise a different composition than dielectric layer 444 on rear electrode 432. In an exemplary embodiment, dielectric layers 442, 444 may comprise two or more sub-layers of dielectric materials.

The sub-layers may comprise different materials. For example, front dielectric layer 442 or rear dielectric layer 444 may comprise a sub-layer of SiO_2 and a second sub-layer of polyimide. The dielectric layers may be substantially uniform, continuous and substantially free of surface defects. The dielectric layers may be at least about 0.05nm (*i.e.*, approximately a monolayer) in thickness or more. In some embodiments, the dielectric layer thicknesses may be in the range of about 1-300nm. In other embodiments, the dielectric layer thicknesses may be in the range of about 1-200nm. In still other embodiments, the dielectric layer thicknesses may be about 1-100nm. In still other embodiments, the dielectric layer thicknesses may be about 1-50nm. In still other embodiments, the dielectric layer thicknesses may be about 1-20nm. In still other embodiments, the dielectric layer thicknesses may be about 1-10nm. The dielectric layers may comprise at least one pin hole. The dielectric layer may define a conformal coating and may be free of pin holes or may have minimal pin holes. The dielectric layer may also act as a barrier layer to prevent moisture or gas ingress. The dielectric layers may have a high or low dielectric constant.

In some embodiments, the dielectric layers may have a dielectric constant in the range of about 1-30. In other embodiments, the dielectric layers may have a dielectric constant in the range of about 1-15.

Dielectric compounds may be organic or inorganic in type. The most common inorganic dielectric material is SiO_2 commonly used in integrated chips. The dielectric layer may be SiN, SiN_x or SiON. The dielectric layer may be AlO_x or Al_2O_3. The dielectric layer may be a ceramic. Organic dielectric materials are typically polymers such as polyimides, fluoropolymers, polynorbornenes and hydrocarbon-based polymers lacking polar groups. The dielectric layers may be a polymer or a combination of polymers. The dielectric layers may be combinations of polymers, metal oxides and ceramics. Dielectric layers 442, 444 may comprise one or more of the following polyimide-based dielectrics Dalton DL-5260T, TC-139, DL-2193, Nissan SE-150, SE-410, SE-610, SE-3140N, SE-3310, SE-3510, SE-5661, SE-5811, SE-6414, SE-6514, SE-7492, SE-7992 or JSR AL-1054, AL-3046, AL22620, AL16301, AL60720. In an exemplary embodiment, the dielectric layers comprise Parylene. In other embodiments the dielectric layers may comprise a halogenated Parylene. Dielectric layers 442, 444 may comprise Parylene C, Parylene N, Parylene F, Parylene HT or Parylene HTX. Other inorganic or organic dielectric materials or combinations thereof may also be used for the dielectric layers. One or more of the dielectric layers may be CVD, PECVD or sputter coated. One or more of dielectric layers 442, 444 may be a solution coated polymer, vapor deposited dielectric, sputter deposited or thermal or plasma enhanced ALD dielectric. Dielectric layer 444 may be conformal to rear electrode structures or could be used to planarize the electrode structures. Planarization of the electrode structures leading to a smoother and more even surface may allow for deposition of sidewalls with more uniform height and thicknesses.

In an exemplary embodiment, one or more dielectric layers 442 on front electrode 428 or the one or more dielectric layers 444 on rear electrode 432 in rigid, flexible or conformable TIR-based image display 400 may be deposited by the method of thermal or plasma enhanced atomic layer deposition (ALD). ALD may also be referred to as atomic layer epitaxy (ALE), atomic layer growth (ALG), molecular layer epitaxy (MLE), molecular layering (ML) and atomic layer CVD (ALCVD). In an exemplary embodiment, one or both of dielectric layers 442, 444 may comprise ALD coated SiO_2, SiO_x, SiN, SiN_x or SiON. Dielectric layers 442, 444 may comprise other metal oxides such as one or more of Al_2O_3, AlO_x, CaO, CuO, Er_2O_3, Ga_2O_3, HfO_2, HfO_x, InZnO, InGaZnO, La_2O_3, MgO, Nb_2O_5, Sc_2O_3, SnO_2, Ta_2O_5, TiO_2, V_XO_Y, Y_2O_3, Yb_2O_3, $ZnSnO_x$, ZnO or ZrO_2. Dielectric layers 442, 444 may comprise one or more metal nitrides such as AlN, BN, GaN, SiN, SiN_x, TaN, TaN_X, TiAlN, TiN, WN or TiN_X. Dielectric layers 442, 444 may comprise a combination of metal oxides and metal nitrides.

At least one edge seal may be employed with the disclosed display embodiments. The edge seal may prevent ingress of moisture or other environmental contaminants from entering the display. The edge seal may be a thermally, chemically or a radiation cured material or a combination thereof. The edge seal may comprise one or more of an epoxy, silicone, polyisobutylene, acrylate or other polymer based material. In some embodiments the edge seal may comprise a metallized foil. In some embodiments the edge sealant may comprise a filler such as SiO_2 or Al_2O_3. In other embodiments, the edge seal may be flexible or conformable after curing. In still other embodiments, the edge seal may also act as a barrier to moisture, oxygen and other gasses.

Display embodiment 400 may further comprise a voltage bias source 446. Bias source 446 may be used to create an electric field or electromagnetic flux in gap 434 formed between front electrode 428 and rear electrode 432. The flux may extend to any medium 438 disposed in gap 434. The flux may move at least one of particles 440 towards one electrode and away from the opposing electrode. The flux may move one or more particles into the evanescent wave region or out of the evanescent wave region. The evanescent wave region approximately resides at the interface of high refractive index facets 408 and lower refractive index medium 438.

Bias source 446 may be coupled to one or more processor circuitry and memory circuitry configured to change or switch the applied bias in a predefined manner and/or for predetermined durations. For example, the processing circuity may switch the applied bias to display characters on display 400. The processing and the memory circuity may comprise hardware, software or a combination of hardware and software. In an exemplary embodiment, one or more of the processing or memory circuitry is flexible and/or conformable. For example, the circuitry may be printed on a flexible substrate to allow flexibility.

Display 400 may further comprise an ambient light sensor (ALS) 450 and front light controller 452. ALS 450 may be used to detect the amount of ambient light available and send the information to front light controller 452. Front light controller 452 may then control the output of light source 424 in front light system 420 depending on the amount of ambient light available. For example, in dim lighting conditions such as at night, ALS 450 may send information to front light controller 452 to increase the amount of light emitted from light source 424 in front light system 420. In bright conditions, such as on a beach on a sunny day, ALS 450 may send information to front light controller 452 to reduce the light output from light source 424 in front light system 420. Reflective displays appear brighter as availability of ambient light increases.

Display embodiment 400 may be operated as follows. A bias may be applied by source 446 of opposite polarity to that of particles 440 at front electrode 428 such that particles 440 are moved towards front electrode 428. This electrophoretically moves particles 440 near front electrode 428 where they may enter the evanescent wave region and frustrate TIR as light rays are reflected between facets 408 and specular reflective surface 410. This is shown to the right of dotted line 454 and is illustrated by incident light rays 456 being absorbed by particles 440. This area of the display may appear as a dark state to viewer 414. All of the particles may not be located on the front electrode as depicted in Fig. 4. The placement of particles 440 in Fig. 4 is for illustrative purposes only.

When particles are moved away from front electrode 428 towards rear electrode 432 (as shown to the left of dotted line 454) incident light rays may be totally internally reflected and specularly reflected at the hybrid retroreflectors 404 described herein. This is represented by first incident light ray 458, which is totally internally reflected at facets 408 then by specular layer 410 then exits the display towards viewer 414 as reflected light ray 460. Another representative reflection mode is illustrated by incident light ray 462. Light ray 462 first reflects by specular reflective surface 410 then is reflected towards facets 408 where the light ray undergoes two TIR-based reflections before being reflected back towards viewer 414 as reflected and exiting light ray 464. In both reflection modes, the display pixel may appear white or bright to the viewer. It should be noted that the location of particles 440 at rear electrode 432 is for illustrative purposes only. Particles 440 may be located just outside of the evanescent wave region near front electrode 428. Particles 440 may be located anywhere within gap 434 such that they do not substantially frustrate TIR when a white state is desired. Gray states may be formed by having a fraction of particles 440 in the evanescent wave region at layer 428 and another fraction of particles outside of the evanescent wave region in gap 434.

It is important to note that the geometry of the hybrid retroreflector system described herein hybridizes TIR and specular reflection. TIR can be switched on and off by the movement of electrophoretically mobile particles 440 while specular reflection, in this geometry, cannot be controlled by the movement of the absorbing material. The goal of this invention is to achieve a switchable display, and the hybridization of TIR and specular reflection is one of the reasons why this invention is not obvious. The specular reflection components are required to cause the light to be retroreflected as desired, and yet the specular component cannot be switched off. There is a vast number of permutations of hierarchical microstructures making use of combinations of TIR and specular surfaces. The geometry of the hybrid retroreflector invention described herein that, for a usefully wide range of viewing angles (in this case approximately +/-40 degrees from normal incidence), retroreflects virtually all of the light incident within the useful viewing range and for which frustration of the TIR essentially eliminates, through absorption, all of the reflected light within that range. This is despite the fact that specular reflection persists, since it cannot be absorbed. It is not obvious that it could be possible to achieve an adequately dark black state for a display that includes a non-switchable specular reflection. A further advantage of the invention described herein is that the geometry arises from the fact that each reflected light ray undergoes two reflections by TIR. This means that it is possible to get significant attenuation of the reflected light with only a moderate degree of frustration of the reflected light.

It is important to further note that the retroreflector design described herein may, via a cursory look, appear similar to prior art retroreflector designs described in patents US2216325 (referred to as "Ryder") and US9575225 (referred to as "Kim"). There are distinct differences that makes the retroreflector designs described herein unique and much better suited for use in static and switchable image displays that are also described herein. Firstly, Ryder and Kim's designs would not be efficient retroreflectors if the plastic structures they described were in contact with a particle-suspending, fluorinated hydrocarbon fluid medium instead of air. This is because the critical angle (θ_c) for TIR would no longer be met at one or more of the structure facets (i.e., 206, 308, 408). Secondly, Ryder and Kim do not describe the use of partial metallization to cause specular reflection at one or more of the structure facets. Lastly, the retroreflectors described by Ryder and Kim were not designed to be switchable retroreflectors, thus they do not describe a method of frustrating TIR or the use of a fluorinated hydrocarbon fluid. The fluorinated hydrocarbon fluid is needed to provide a medium to suspend the electrophoretically mobile particles and to provide a low refractive index fluid medium to be in contact with the higher refractive index retroreflector. This allows for a method to enable a switchable display and for a lower θ_c to allow for more light to be totally internally reflected leading to a brighter display.

In a switchable image display (*i.e.*, 400) whereby the reflection of incident light is prevented by means of frustrated TIR, a fluid, such as a fluorinated hydrocarbon fluid, is needed to provide a medium to suspend the electrophoretically mobile particles 440. The retroreflective corner cube structures typically used in conventional retroreflective signage applications are not suitable for a switchable image display wherein corner cube structures are in contact with a fluorinated hydrocarbon fluid, particle-suspending medium instead of air. This is because the critical angle (θ_c) for TIR would no longer be met at one or more of the structure facets and as a result the incident light would not be efficiently reflected.

Various control mechanisms for the invention may be implemented fully or partially in software and/or firmware. This software and/or firmware may take the form of instructions contained in or on a non-transitory computer-readable storage medium. Those instructions may then be read and executed by one or more processors to enable performance of the operations described herein. The instructions may be in any suitable form, such as but not limited to source code, compiled code, interpreted code, executable code, static code, dynamic code and the like. Such a computer-readable medium may include any tangible non-transitory medium for storing information in a form readable by one or more computers, such as but not limited to read only memory (ROM); random access memory (RAM); magnetic disk storage media; optical storage media; flash memory, etc.

In some embodiments, a tangible machine-readable non-transitory storage medium that contains instructions may be used in combination with the disclosed display embodiments. In other embodiments the tangible machine-readable non-transitory storage medium may be further used in combination with one or more processors.

Fig. 6 shows an exemplary system for controlling a display according to one embodiment of the disclosure. In Fig. 6, display 400 is controlled by controller 640 having processor 630 and memory 620. Other control mechanisms and/or devices may be included in controller 640 without departing from the disclosed principles. Controller 640 may define hardware, software or a combination of hardware and software. For example, controller 640 may define a processor programmed with instructions (*e.g.*, firmware). Processor 630 may be an actual processor or a virtual processor. Similarly, memory 620 may be an actual memory (*i.e.*, hardware) or virtual memory (*i.e.*, software).

Memory 620 may store instructions to be executed by processor 630 for driving display 400. The instructions may be configured to operate display 400. In one embodiment, the instructions may include biasing electrodes associated with display 400 through power supply 650. When biased, the electrodes may cause movement of electrophoretic particles towards or away from a region proximal to the surface of the plurality of non-coated facets 408 at the inward surface of the front transparent sheet to thereby absorb or reflect light received at the inward surface of the front transparent sheet. By appropriately biasing the electrodes, particles (*e.g.*, particles 440 in Fig. 4) may be moved near the surface of the plurality of non-coated facets 408 at the inward surface of the front transparent sheet into or near the evanescent wave region in order to substantially or selectively absorb or reflect the incoming light. Absorbing the incoming light creates a dark or colored state. By appropriately biasing the electrodes, particles (*e.g.*, particles 444 in Fig. 4) may be moved away from the surface of the plurality of facets 408 at the inward surface of the front transparent sheet and out of the evanescent wave region in order to reflect or absorb the incoming light. Reflecting the incoming light creates a light state.

In the exemplary display embodiments described herein, they may be used in Internet of Things (IoT) devices. The IoT devices may comprise a local wireless or wired communication interface to establish a local wireless or wired communication link with one or more IoT hubs or client devices. The IoT devices may further comprise a secure communication channel with an IoT service over the internet using a local wireless or wired communication link. The IoT devices comprising one or more of the display devices described herein may further comprise a sensor. Sensors may include one or more of a temperature, humidity, light, sound, motion, vibration, proximity, gas or heat sensor. The IoT devices comprising one or more of the display devices described herein may be interfaced with home appliances such as a refrigerator, freezer, television (TV), close captioned TV (CCTV), stereo system, heating, ventilation, air conditioning (HVAC) system, robotic vacuum, air purifiers, lighting system, washing machine, drying machine, oven, fire alarms, home security system, pool equipment, dehumidifier or dishwashing machine. The IoT devices comprising one or more of the display devices described herein may be interfaced with health monitoring systems such as heart monitoring, diabetic monitoring, temperature monitoring, biochip transponders or pedometer. The IoT devices comprising one or more of the display devices described herein may be interfaced with transportation monitoring systems such as those in an automobile, motorcycle, bicycle, scooter, marine vehicle, bus or airplane.

In the exemplary display embodiments described herein, they may be used in IoT and non-IoT applications such as in, but not limited to, electronic book readers, portable computers, tablet computers, cellular telephones, smart cards, signs, watches, wearables, military display applications, automotive displays, automotive license plates, shelf labels, flash drives and outdoor billboards or outdoor signs comprising a display. The displays may be powered by one or more of a battery, solar cell, wind, electrical generator, electrical outlet, AC power, DC power or other means.

In the exemplary static display embodiments described herein, they may be used as reflective clothing, bicycle reflectors, motorized vehicle reflectors, signs, road markings, outdoor billboards, traffic signs, wall signs, advertising signs, emergency signs or outdoor signs.

It will be apparent to those skilled in the technology of image displays that numerous changes and modifications can be made in the preferred embodiments of the invention described above without departing from the scope of the invention. Accordingly, the foregoing description is to be construed in an illustrative and not in a limitative sense.

The following examples are provided to further illustrate different embodiments of the disclosed principles. These examples are non-limiting.

Example 1 is directed to a retroreflector, comprising: one or more light reflecting repeat units, wherein the repeat units comprise; a first facet; a second facet that is substantially orthogonal to the first facet; and a third facet that further comprises a light reflecting coating and is substantially orthogonal to the first facet and the second facet.

Example 2 is directed the retroreflector of claim 1, wherein the first facet and the second facet are comprised of a transparent material having a first refractive index and reflects incident light by means of total internal reflection when in contact with a medium with a lower second refractive index and when the angle of incident light on the first or second facet exceeds the critical angle, θ_c.

Example 3 is directed to the retroreflector of example 1, wherein the light reflecting coating comprises a metal.

Example 4 is directed to the retroreflector of example 1, wherein the light reflecting coating comprises aluminum, silver, copper, gold, nickel or chromium.

Example 5 is directed to the retroreflector of example 2, wherein the first refractive index is in the range of 1.5-2.2.

Example 6 is directed to the retroreflector of example 2, wherein the first refractive index is in the range of 1.6-1.9.

Example 7 is directed to the retroreflector of example 1, wherein an angle is formed between the first facet and the second facet and is in the range of 85-95 degrees.

Example 8 is directed to the retroreflector of example 1, wherein an angle is formed between the first facet and the third facet and is in the range of 85-95 degrees.

Example 9 is directed to the retroreflector of example 1, wherein an angle is formed between the second facet and the third facet and is in the range of 85-95 degrees.

Example 10 is directed to a retroreflector, comprising: one or more prisms, wherein the prisms further comprise; a first facet further comprising smaller prisms; and a second facet that is arranged orthogonal to the smaller prisms of the first facet and further comprising a specularly reflecting coating.

Example 11 is directed to the retroreflector of example 10, wherein the first facet is comprised of a transparent material having a first refractive index and totally internally reflects incident light when in contact with a medium with a lower second refractive index and when the angle of incident light on the first facet exceeds the critical angle, θ_c.

Example 12 is directed to the retroreflector of example 10, wherein the light reflecting coating comprises a metal.

Example 13 is directed to the retroreflector of example 10, wherein the light reflecting coating comprises aluminum, silver, copper, gold, nickel or chromium.

Example 14 is directed to the retroreflector of example 10, wherein an angle is formed between the first facet and the second facet and is in the range of 85-95 degrees.

Example 15 is directed to a totally internally reflective ("TIR") display, comprising: a transparent front sheet; a plurality of light reflecting repeat units positioned over the inward surface of the transparent front sheet, each repeat unit comprising a first, second and third facet, wherein the first and second facets are comprised of a material with a first refractive index; a light reflecting coating on the third facet of each light reflecting repeat unit; one or more front electrodes formed over the light reflecting repeat units; one or more rear electrodes positioned to form a gap with the front electrode; and a plurality of electrophoretically mobile particles suspended in a medium disposed in the gap wherein the medium has a second refractive index lower than the first refractive index of the material comprising the first and second facets.

Example 16 is directed to the TIR display of example 15, further comprising a plurality of color filter sub-pixels positioned over the outward surface of the transparent front sheet.

Example 17 is directed to the TIR display of example 15, further comprising a dielectric layer positioned over one or both of the front and rear electrodes.

Example 18 is directed to the TIR display of example 15, further comprising at least one pixel wall positioned in the gap.

Example 19 is directed to the TIR display of example 15, wherein the electrophoretically mobile particles are suspended in a fluorinated medium.

Example 20 is directed to the TIR display of example 15, further comprising a voltage bias source to apply a bias across the gap between the front electrode and the rear electrode to move at least one electrophoretically mobile particle near the surface of the first and second facets to frustrate total internal reflection of light.

Example 21 is directed to the TIR display of example 15, wherein the material with a first refractive index comprises a refractive index in the range of 1.5-2.2.

Example 22 is directed to the TIR display of example 15, wherein the material with a first refractive index comprises a refractive index in the range of 1.6-1.9.

Example 23 is directed to the TIR display of example 15, further comprising at least one dielectric layer located on the front or rear electrode.

Example 24 is directed to the TIR display of example 15, further comprising a front light system.

Example 25 is directed to the TIR display of example 15, further comprising a barrier layer.

Example 26 is directed to the TIR display of example 15, further comprising an edge seal.

Example 27 is directed to the TIR display of example 15, wherein an angle is formed between the first facet and the second facet and is in the range of 85-95 degrees.

Example 28 is directed to the TIR display of example 15, wherein an angle is formed between the first facet and the third facet and is in the range of 85-95 degrees.

Example 29 is directed to the TIR display of example 15, wherein an angle is formed between the second facet and the third facet and is in the range of 85-95 degrees.

Example 30 is directed to a totally internally reflective ("TIR") display, comprising: a transparent front sheet; a plurality of prisms positioned over the inward surface of the transparent front sheet, wherein the prisms further comprise; a first facet further comprising smaller prisms and composed of a material with a first refractive index; a second facet that is arranged orthogonal to the smaller prisms of the first facet and further comprising a light reflecting coating; one or more front electrodes formed over the plurality of prisms; one or more rear electrodes positioned to form a gap with the front electrode; and a plurality of electrophoretically mobile particles suspended in a medium disposed in the gap wherein the medium has a second refractive index lower than the first refractive index of the material comprising the first facet.

Example 31 is directed to the TIR display of example 30, further comprising a plurality of color filter sub-pixels positioned over the outward surface of the transparent front sheet.

Example 32 is directed to the TIR display of example 30, further comprising a dielectric layer positioned over one or both of the front and rear electrodes.

Example 33 is directed to the TIR display of example 30, further comprising at least one pixel wall positioned in the gap.

Example 34 is directed to the TIR display of example 30, wherein the electrophoretically mobile particles are suspended in a fluorinated medium.

Example 35 is directed to the TIR display of example 30, further comprising a voltage bias source to apply a bias across the gap between the front electrode and the rear electrode to move at least one electrophoretically mobile particle near the surface of the prisms of the first facet to frustrate total internal reflection of light.

Example 36 is directed to the TIR display of example 30, wherein the prisms comprise a refractive index in the range of 1.5-2.2.

Example 37 is directed to the TIR display of example 30, wherein the prisms comprise a refractive index in the range of 1.6-1.9.

Example 38 is directed to the TIR display of example 30, further comprising at least one dielectric layer located on the front or rear electrode.

Example 39 is directed to the TIR display of example 30, further comprising a front light system.

Example 40 is directed to the TIR display of example 30, further comprising a barrier layer.

Example 41 is directed to the TIR display of example 30, further comprising an edge seal.

Example 42 is directed to the TIR display of example 30, wherein an angle is formed between the first facet and second facet and is in the range of 85-95 degrees.

Example 43 is directed to a method for switching a TIR image display from a light state to a dark state, comprising: applying a first non-zero voltage to attract a plurality of electrophoretically mobile particles towards the front electrode that is positioned over light reflecting repeat units; the electrophoretically mobile particles enter the evanescent wave region near the surface of a facet of a light reflecting repeat unit that does not comprise a light reflective coating; and wherein total internal reflection of incident light is frustrated and light is absorbed by the electrophoretically mobile particles to form a dark state.

While the principles of the disclosure have been illustrated in relation to the exemplary embodiments shown herein, the principles of the disclosure are not limited thereto and include any modification, variation or permutation thereof.

What is claimed is:

1. A retroreflector, comprising:

one or more light reflecting repeat units, wherein the repeat units comprise;

a first facet;

a second facet that is substantially orthogonal to the first facet; and

a third facet that further comprises a light reflecting coating and is substantially orthogonal to the first facet and the second facet.

2. The retroreflector of claim 1, wherein the first facet and the second facet are comprised of a transparent material having a first refractive index and reflects incident light by means of total internal reflection when in contact with a medium with a lower second refractive index and when the angle of incident light on the first or second facet exceeds the critical angle, θ_c.

3. The retroreflector of claim 1, wherein the light reflecting coating comprises a metal.

4. The retroreflector of claim 1, wherein the light reflecting coating comprises aluminum, silver, copper, gold, nickel or chromium.

5. The retroreflector of claim 2, wherein the first refractive index is in the range of 1.5-2.2.

6. The retroreflector of claim 2, wherein the first refractive index is in the range of 1.6-1.9.

7. The retroreflector of claim 1, wherein an angle is formed between the first facet and the second facet and is in the range of 85-95 degrees.

8. The retroreflector of claim 1, wherein an angle is formed between the first facet and the third facet and is in the range of 85-95 degrees.

9. The retroreflector of claim 1, wherein an angle is formed between the second facet and the third facet and is in the range of 85-95 degrees.

10. A retroreflector, comprising:

one or more prisms, wherein the prisms further comprise;

a first facet further comprising smaller prisms; and

a second facet that is arranged orthogonal to the smaller prisms of the first facet and further comprises a light reflecting coating;

11. The retroreflector of claim 10, wherein the first facet is comprised of a transparent material having a first refractive index and totally internally reflects incident light when in contact with a medium with a lower second refractive index and when the angle of incident light on the first facet exceeds the critical angle, θ_c.

12. The retroreflector of claim 10, wherein the light reflecting coating comprises a metal.

13. The retroreflector of claim 10, wherein the light reflecting coating comprises aluminum, silver, copper, gold, nickel or chromium.

14. The retroreflector of claim 10, wherein an angle is formed between the first facet and the second facet and is in the range of 85-95 degrees.

15. A totally internally reflective ("TIR") display, comprising:

a transparent front sheet;

a plurality of light reflecting repeat units positioned over the inward surface of the transparent front sheet, each repeat unit comprising a first, second and third facet, wherein the first and second facets are comprised of a material with a first refractive index;

a light reflecting coating on the third facet of each light reflecting repeat unit;

one or more front electrodes formed over the light reflecting repeat units;

one or more rear electrodes positioned to form a gap with the front electrode; and

a plurality of electrophoretically mobile particles suspended in a medium disposed in the gap wherein the medium has a second refractive index lower than the first refractive index of the material comprising the first and second facets.

16. The TIR display of claim 15, further comprising a plurality of color filter sub-pixels positioned over the outward surface of the transparent front sheet.

17. The TIR display of claim 15, further comprising a dielectric layer positioned over one or both of the front and rear electrodes.

18. The TIR display of claim 15, further comprising at least one pixel wall positioned in the gap.

19. The TIR display of claim 15, wherein the electrophoretically mobile particles are suspended in a fluorinated medium.

20. The TIR display of claim 15, further comprising a voltage bias source to apply a bias across the gap between the front electrode and the rear electrode to move at least one electrophoretically mobile particle near the surface of the first and second facets to frustrate total internal reflection of light.

21. The TIR display of claim 15, wherein the material with a first refractive index comprises a refractive index in the range of 1.5-2.2.

22. The TIR display of claim 15, wherein the material with a first refractive index comprises a refractive index in the range of 1.6-1.9.

23. The TIR display of claim 15, further comprising at least one dielectric layer located on the front or rear electrode.

24. The TIR display of claim 15, further comprising a front light system.

25. The TIR display of claim 15, further comprising a barrier layer.

26. The TIR display of claim 15, further comprising an edge seal.

27. The TIR display of claim 15, wherein an angle is formed between the first facet and the second facet and is in the range of 85-95 degrees.

28. The TIR display of claim 15, wherein an angle is formed between the first facet and the third facet and is in the range of 85-95 degrees.

29. The TIR display of claim 15, wherein an angle is formed between the second facet and the third facet and is in the range of 85-95 degrees.

30. A totally internally reflective (“TIR”) display, comprising:

a transparent front sheet;

a plurality of prisms positioned over the inward surface of the transparent front sheet, wherein the prisms further comprise;

a first facet further comprising smaller prisms and composed of a material with a first refractive index;

a second facet that is arranged orthogonal to the smaller prisms of the first facet and further comprising a light reflecting coating;

one or more front electrodes formed over the plurality of prisms;

one or more rear electrodes positioned to form a gap with the front electrode; and

a plurality of electrophoretically mobile particles suspended in a medium disposed in the gap wherein the medium has a second refractive index lower than the first refractive index of the material comprising the first facet.

31. The TIR display of claim 30, further comprising a plurality of color filter sub-pixels positioned over the outward surface of the transparent front sheet.

32. The TIR display of claim 30, further comprising a dielectric layer positioned over one or both of the front and rear electrodes.

33. The TIR display of claim 30, further comprising at least one pixel wall positioned in the gap.

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34. The TIR display of claim 30, wherein the electrophoretically mobile particles are suspended in a fluorinated medium.

35. The TIR display of claim 30, further comprising a voltage bias source to apply a bias across the gap between the front electrode and the rear electrode to move at least one electrophoretically mobile particle near the surface of the prisms of the first facet to frustrate total internal reflection of light.

36. The TIR display of claim 30, wherein the prisms comprise a refractive index in the range of 1.5-2.2.

37. The TIR display of claim 30, wherein the prisms comprise a refractive index in the range of 1.6-1.9.

38. The TIR display of claim 30, further comprising at least one dielectric layer located on the front or rear electrode.

39. The TIR display of claim 30, further comprising a front light system.

40. The TIR display of claim 30, further comprising a barrier layer.

41. The TIR display of claim 30, further comprising an edge seal.

42. The TIR display of claim 30, wherein an angle is formed between the first facet and second facet and is in the range of 85-95 degrees.

43. A method for switching a TIR image display from a light state to a dark state, comprising:

applying a first non-zero voltage to attract a plurality of electrophoretically mobile particles towards the front electrode that is positioned over light reflecting repeat units;

the electrophoretically mobile particles enter the evanescent wave region near the surface of a facet of a light reflecting repeat unit that does not comprise a light reflective coating; and

wherein total internal reflection of incident light is frustrated and light is absorbed by the electrophoretically mobile particles to form a dark state.

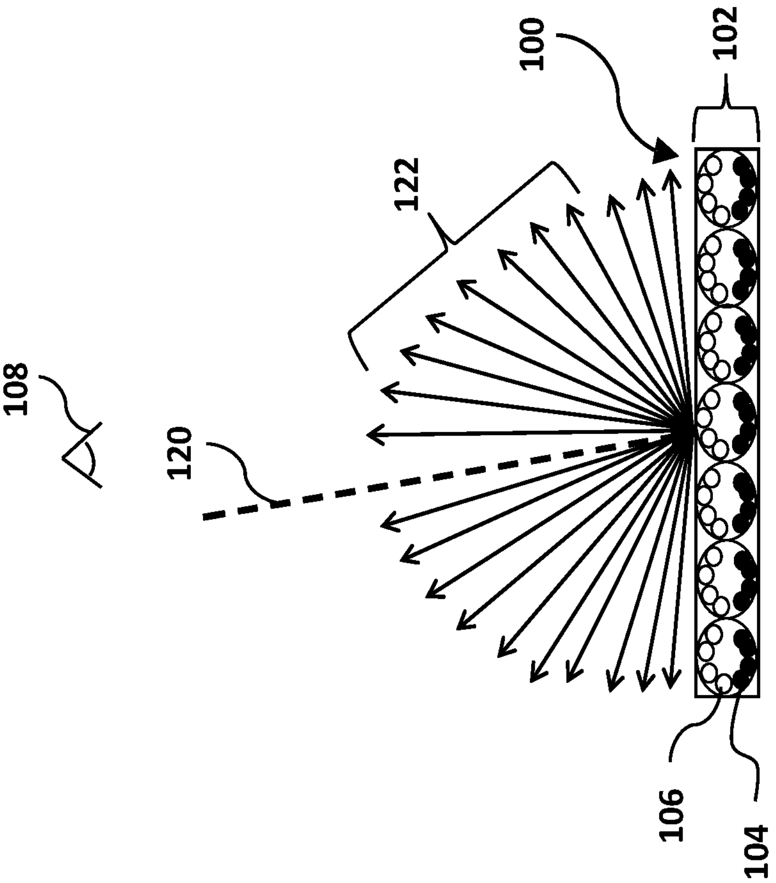
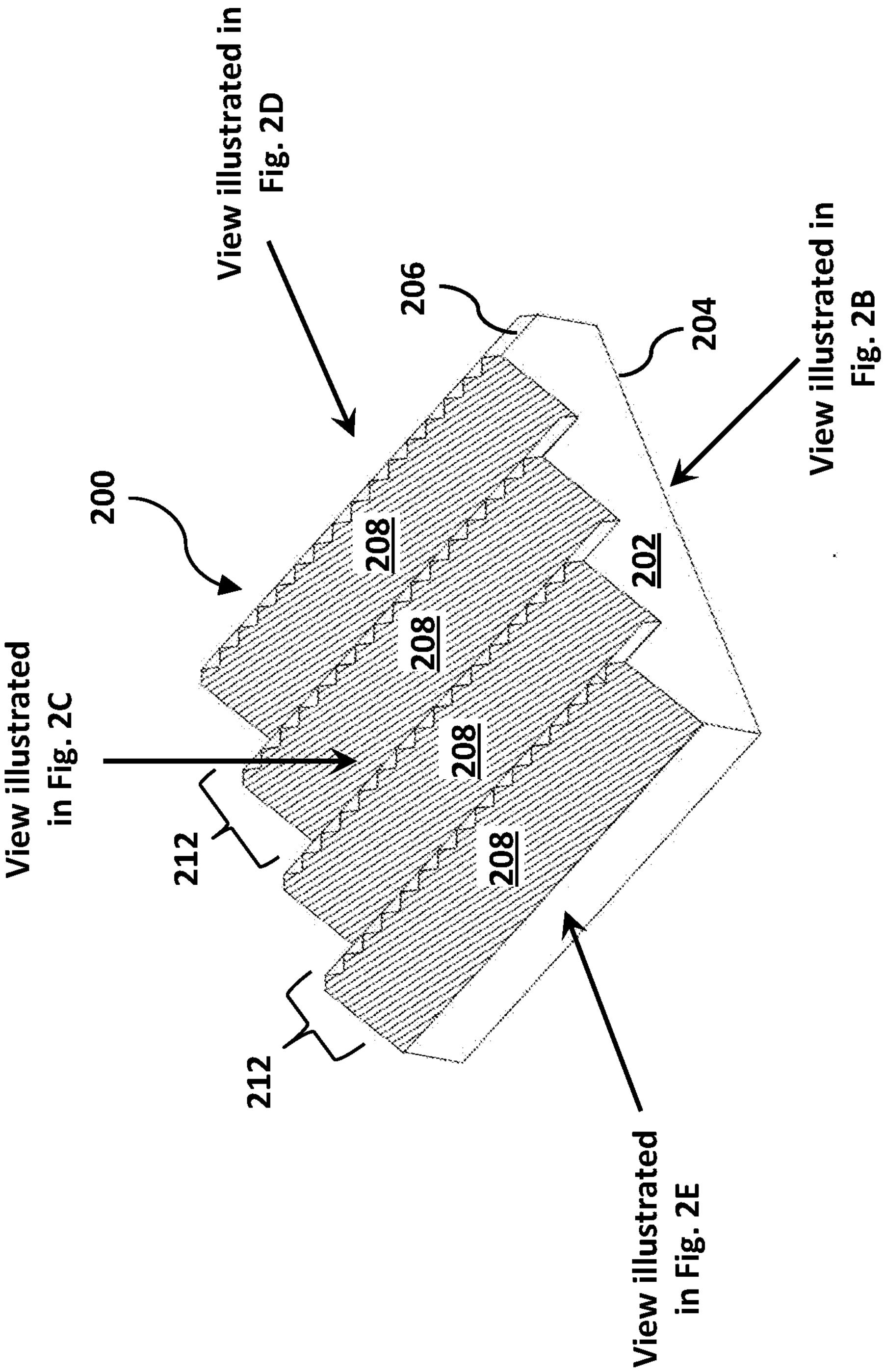


Fig. 1


View illustrated in Fig. 2D
206
204
View illustrated in Fig. 2B
200
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202
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View illustrated in Fig. 2C
212
212
View illustrated in Fig. 2E

Fig. 2A

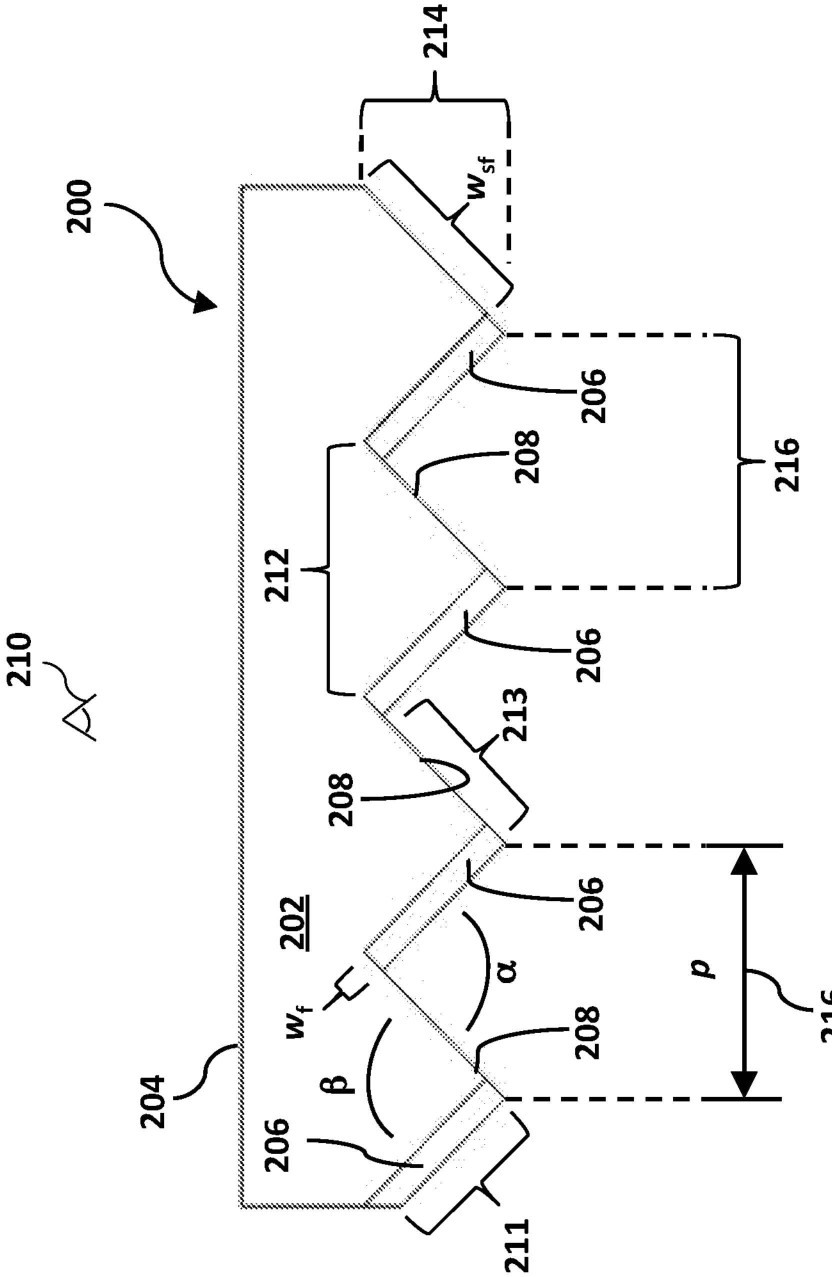
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Fig. 2B

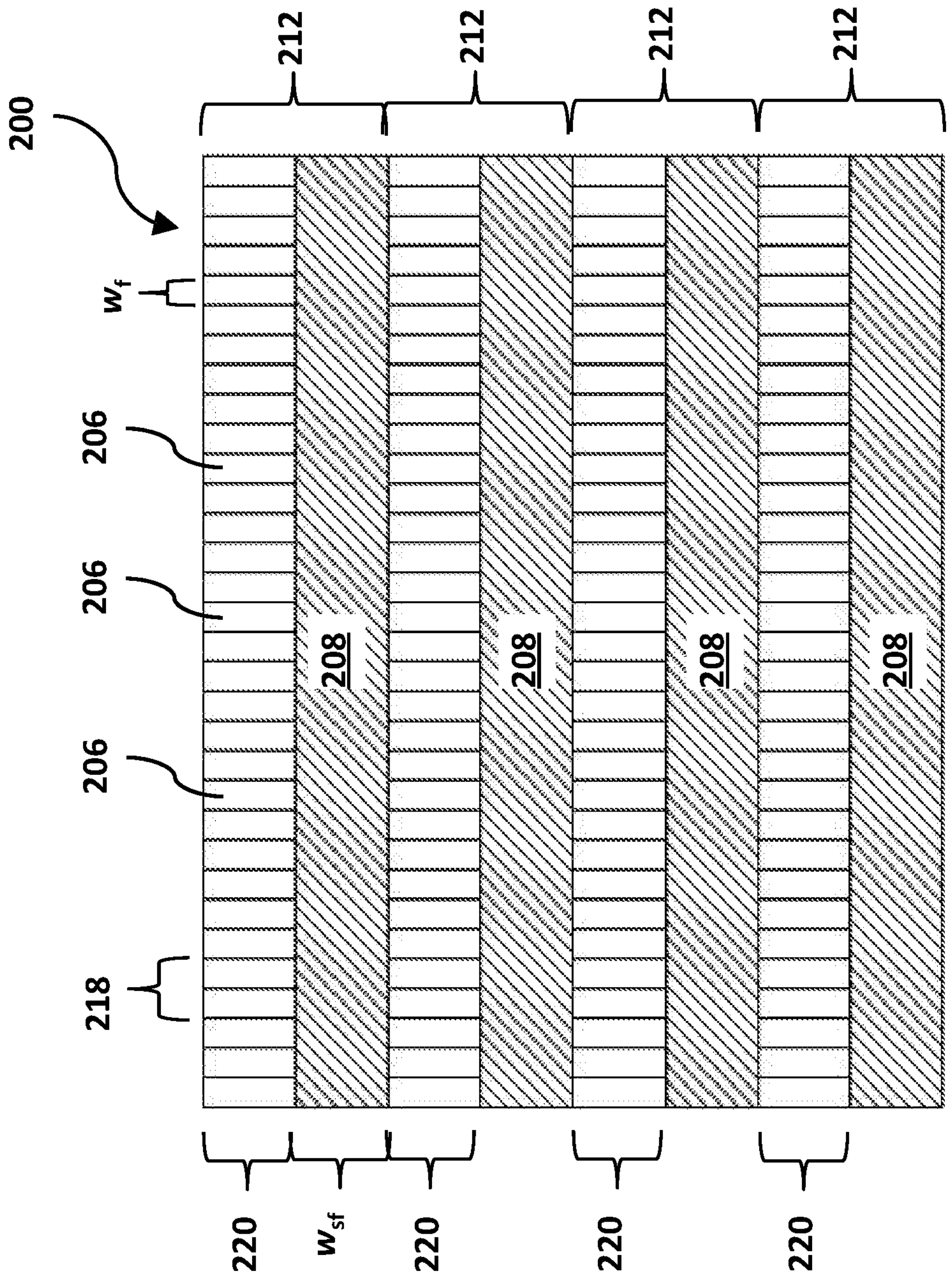
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Fig. 2C

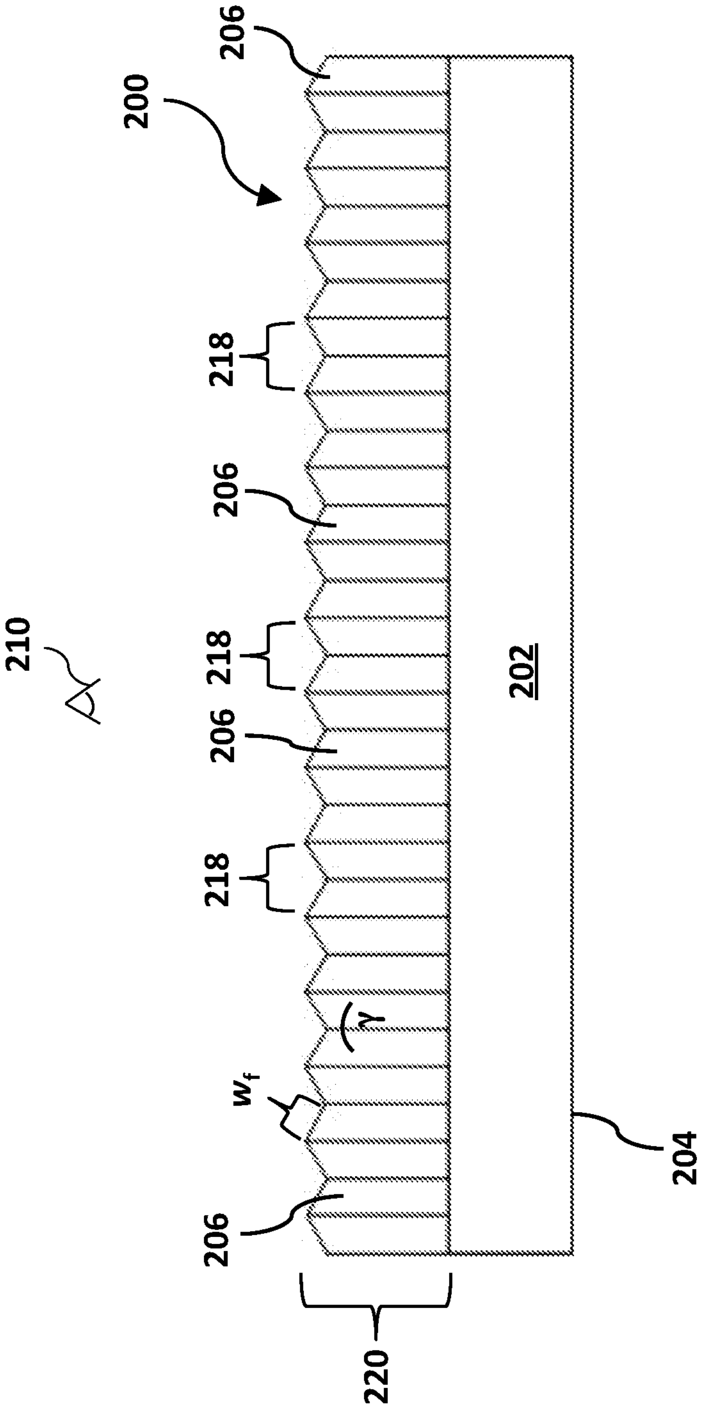

Fig. 2D

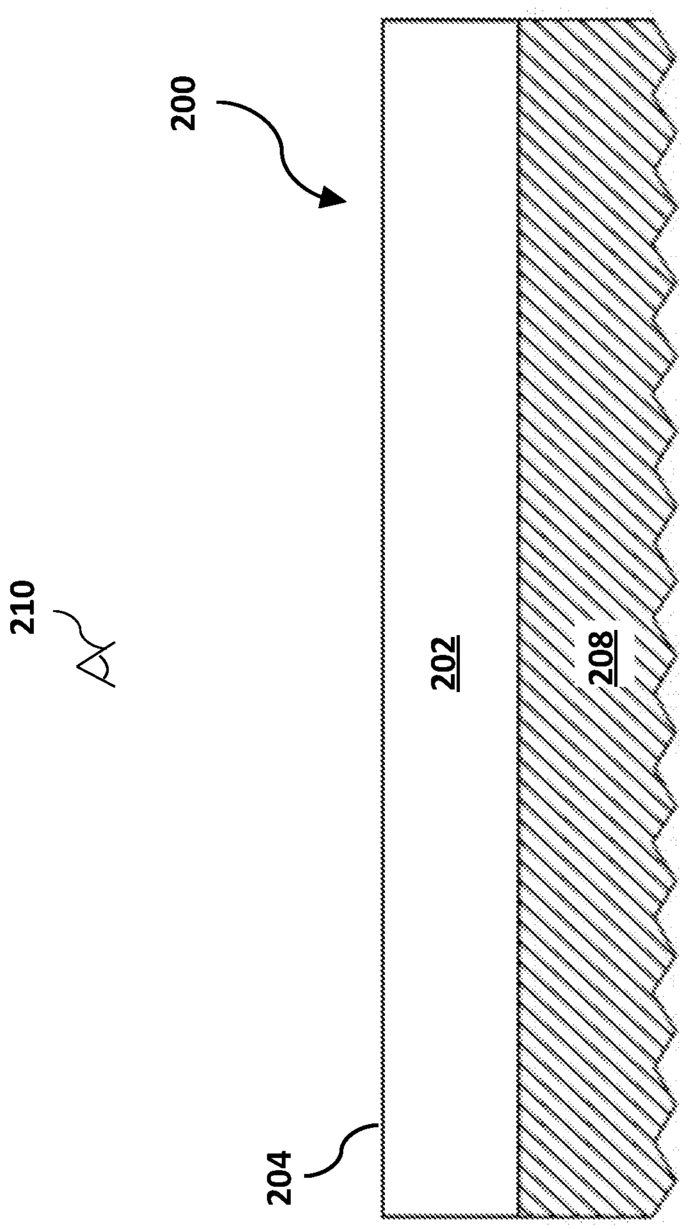

Fig. 2E

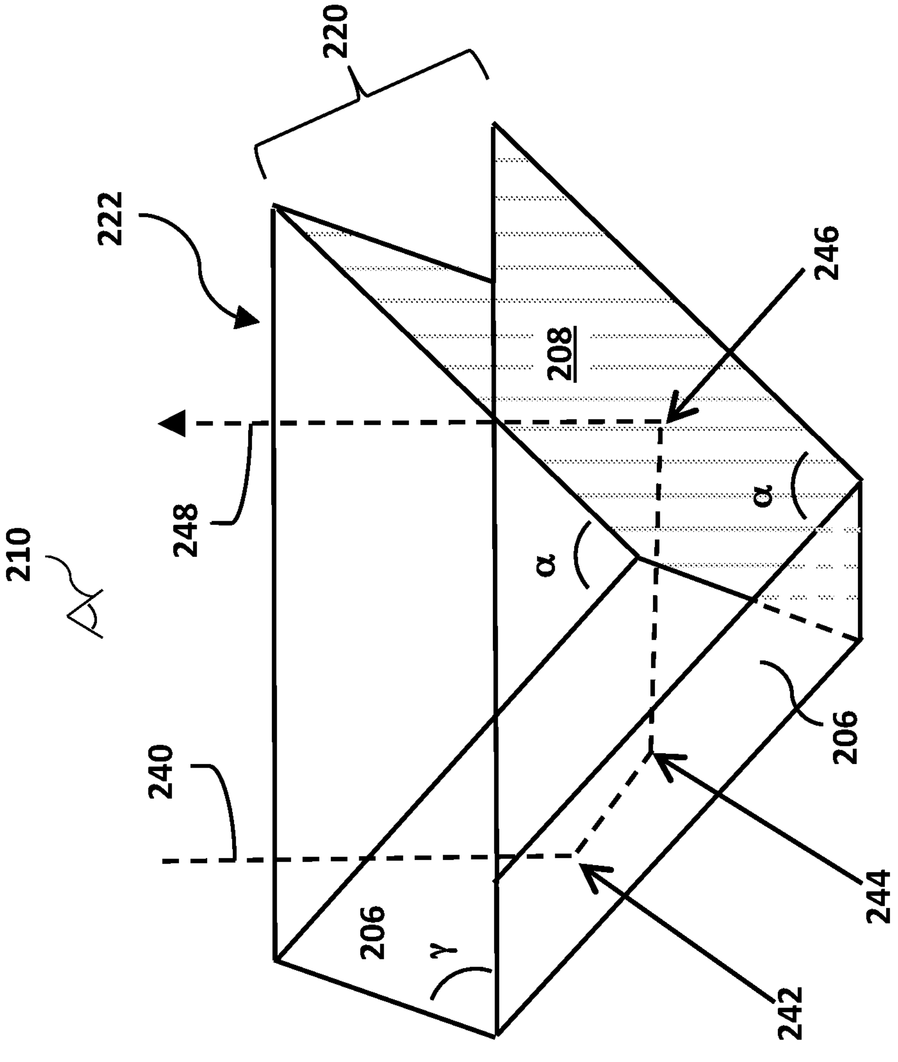

Fig. 2F

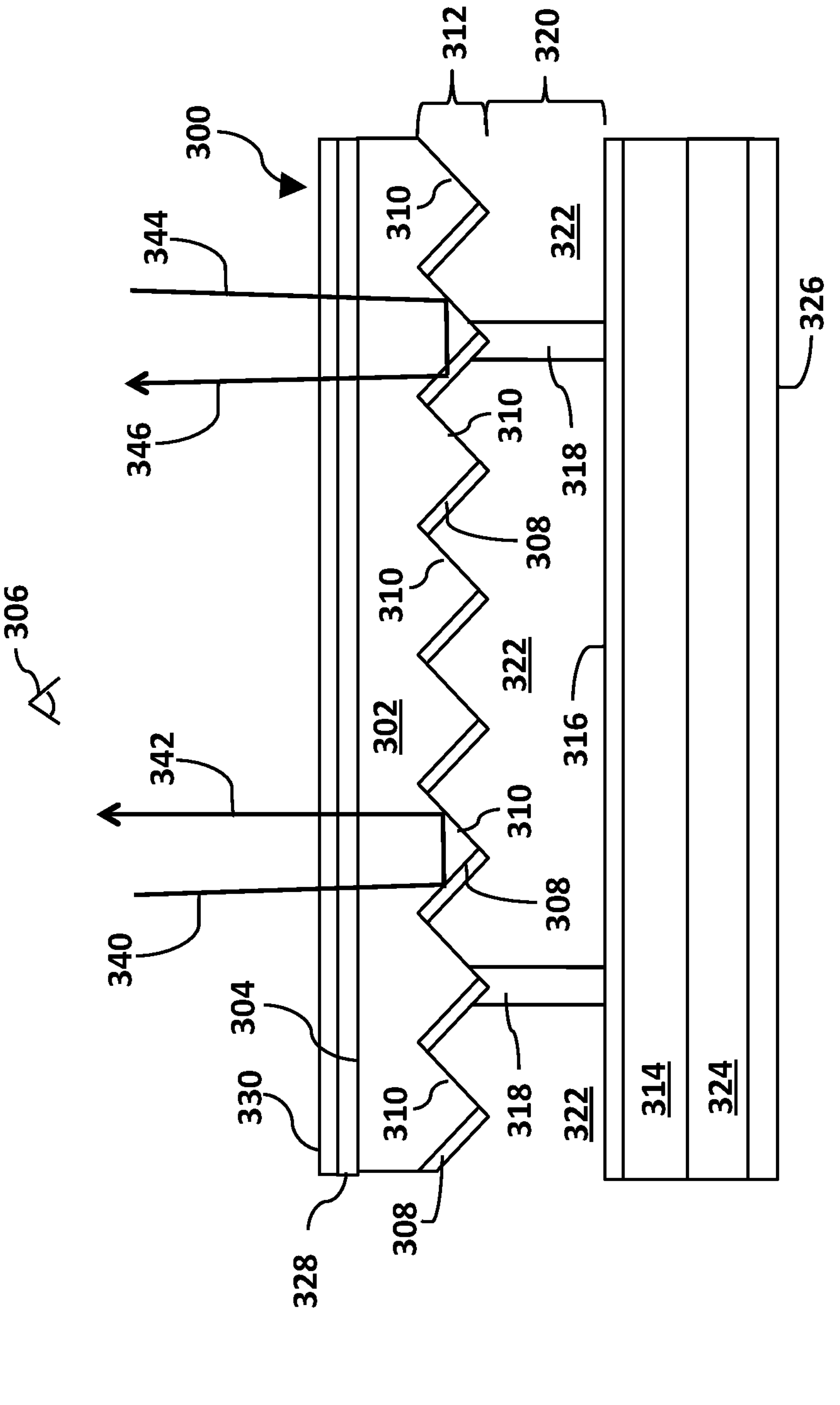
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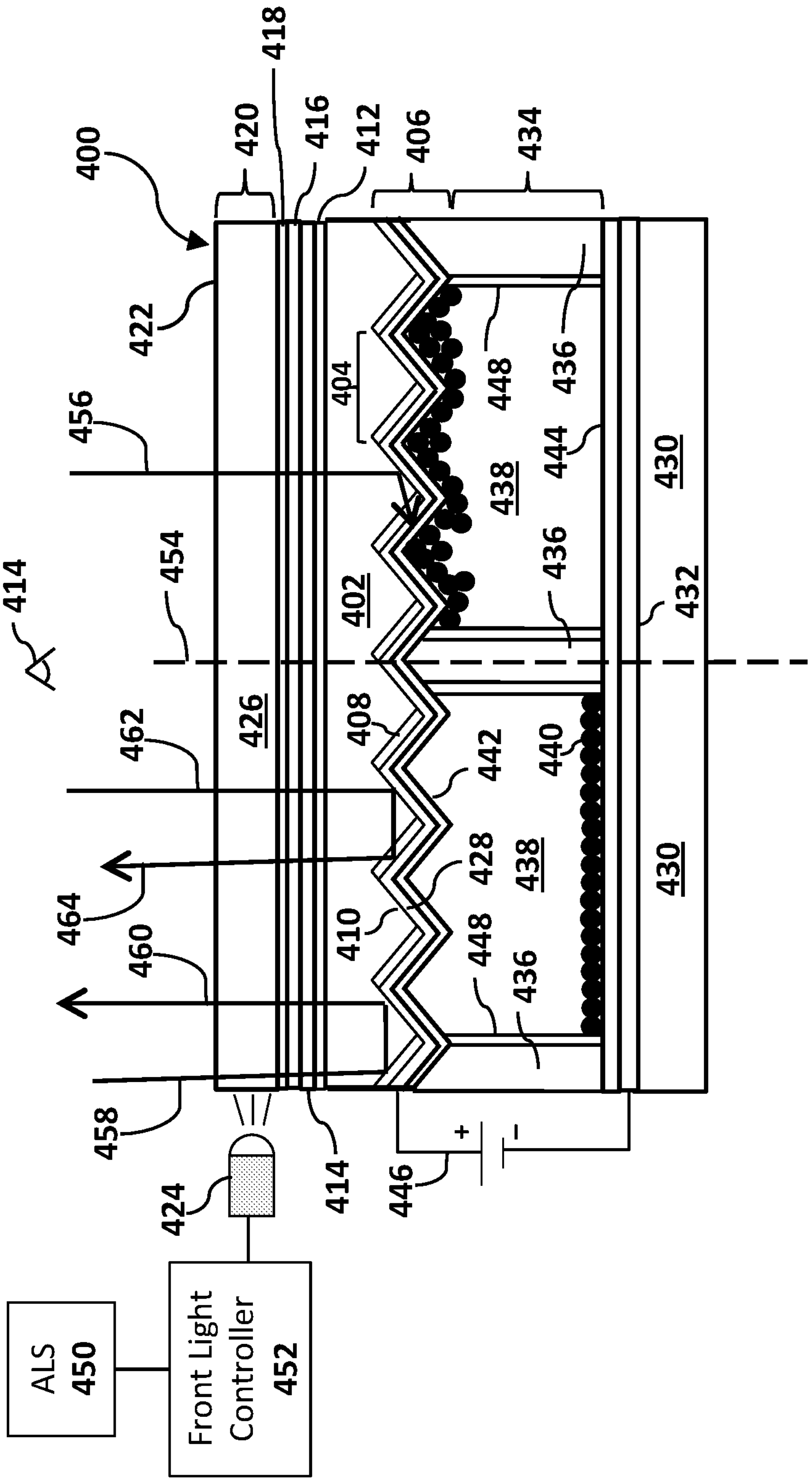
Fig. 3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ALS
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Front Light
Controller
452

Fig. 4

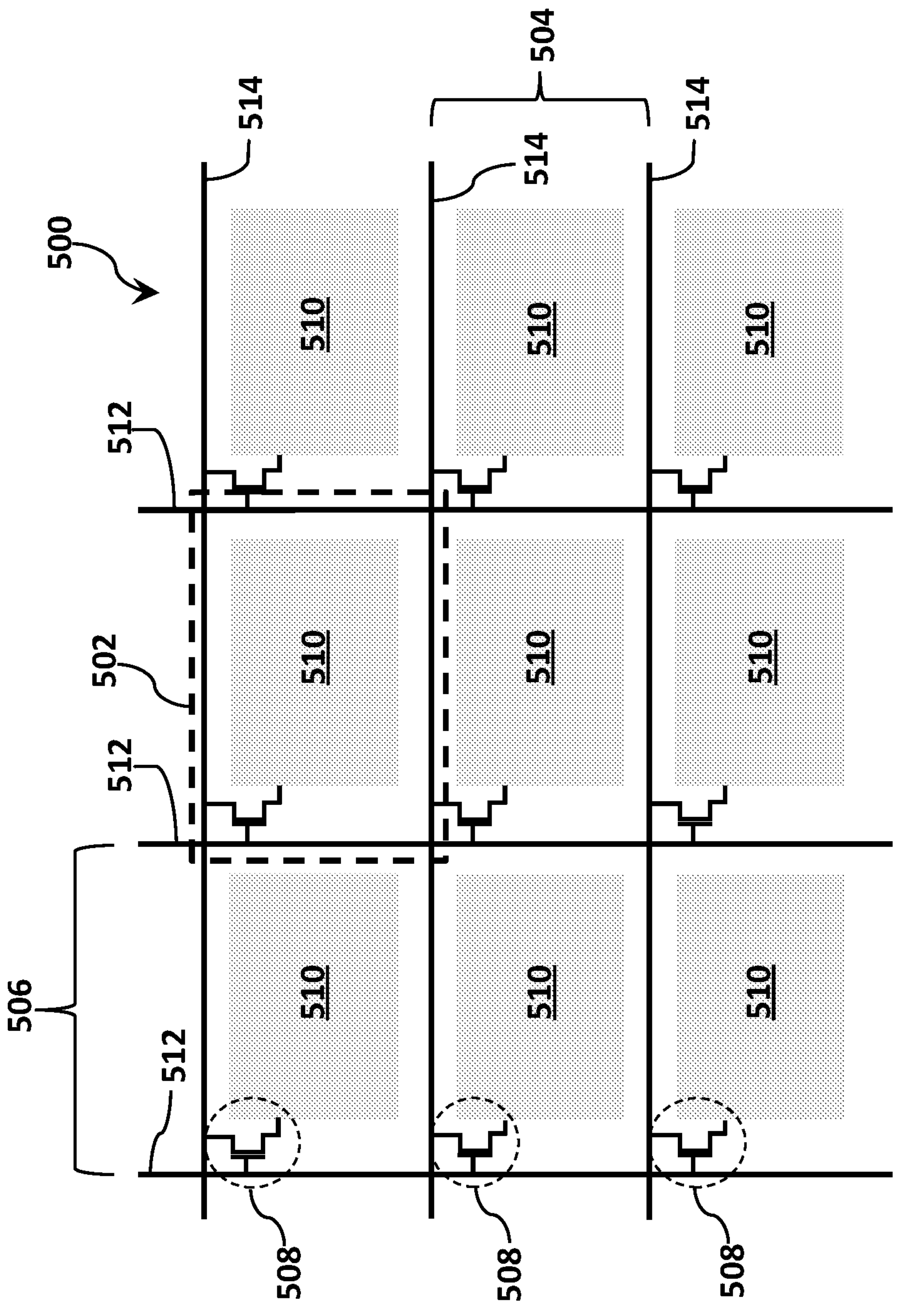

Fig. 5

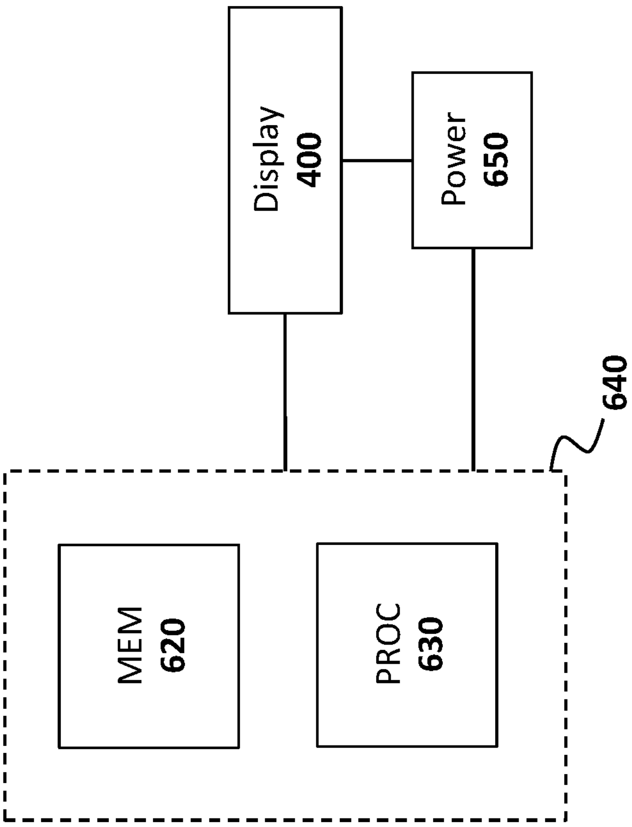

Fig. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/059889

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G02B 5/04; G02B 5/124; G02B 26/08; G02B 27/09; G02F 1/1335 (2020.01)
CPC - G02B 5/124; G02B 5/045; G02B 26/0883; G02B 27/0977; G02F 1/133504 (2020.02)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 359/530 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2006/0158736 A1 (BACON) 20 July 2006 (20.07.2006) entire document	1, 3, 4, 7-9 --- 2, 5, 6, 12, 13
X --- Y	US 2016/0231476 A1 (KIM) 11 August 2016 (11.08.2016) entire document	10, 14 --- 11-13, 30-42
Y	US 6,304,365 B1 (WHITEHEAD) 16 October 2001 (16.10.2001) entire document	2, 5, 6, 11
Y	US 6,215,920 B1 (WHITEHEAD et al) 10 April 2001 (10.04.2001) entire document	30-42
Y	US 2009/0109172 A1 (LEE et al) 30 April 2009 (30.04.2009) entire document	31
Y	US 2018/0031941 A1 (CLEARINK DISPLAYS, INC. et al) 01 February 2018 (01.02.2018) entire document	32, 38, 41
A	US 2012/0275183 A1 (MINAMI et al) 01 November 2012 (01.11.2012) entire document	1-14, 30-42

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 February 2020	11 MAR 2020
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/059889

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See extra sheet(s).

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-14, 30-42

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-14 and 30-42, are drawn to a retroreflector, comprising: the repeat units comprising a first facet; a second facet that is substantially orthogonal to the first facet.

Group II, claims 15-29 and 30-42, are drawn to a totally internally reflective ("TIR") display, comprising: a transparent front sheet.

Group III, claim 43, is drawn to a method for switching a TIR image display from a light state to a dark state, comprising: applying a first non-zero voltage to attract a plurality of electrophoretically mobile particles towards the front electrode.

The inventions listed as Groups I, II and III do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: one or more light reflecting repeat units, wherein the repeat units comprise a first facet; a second facet that is substantially orthogonal to the first facet; and a third facet that further comprises a light reflecting coating and is substantially orthogonal to the first facet and the second facet as claimed therein is not present in the invention of Groups II and III. The special technical feature of the Group II invention: a transparent front sheet; a plurality of light reflecting repeat units positioned over the inward surface of the transparent front sheet, each repeat unit comprising a first, second and third facet, wherein the first and second facets are comprised of a material with a first refractive index; a light reflecting coating on the third facet of each light reflecting repeat unit; one or more front electrodes formed over the light reflecting repeat units; one or more rear electrodes positioned to form a gap with the front electrode; and a plurality of electrophoretically mobile particles suspended in a medium disposed in the gap wherein the medium has a second refractive index lower than the first refractive index of the material comprising the first and second facets as claimed therein is not present in the invention of Groups I or III. The special technical feature of the Group III invention: applying a first non-zero voltage to attract a plurality of electrophoretically mobile particles towards the front electrode that is positioned over light reflecting repeat units; the electrophoretically mobile particles enter the evanescent wave region near the surface of a facet of a light reflecting repeat unit that does not comprise a light reflective coating; and wherein total internal reflection of incident light is frustrated and light is absorbed by the electrophoretically mobile particles to form a dark state as claimed therein is not present in the invention of Groups I or II.

Groups I, II and III lack unity of invention because even though the inventions of these groups require the technical feature a totally internally reflective ("TIR") display, comprising: a plurality of light reflecting repeat units, and a plurality of electrophoretically mobile particles, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2012/0275183 to Minami teaches a totally internally reflective ("TIR") display, comprising: a plurality of light reflecting repeat units, and a plurality of electrophoretically mobile particles (Paras. [0082], [0120], [0128], [0138-0140]).

Since none of the special technical features of the Group I, II or III inventions are found in more than one of the inventions, unity of invention is lacking.