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Novel Directional Projection Screen using Diverted Curved Surfaces Cube Corner Reflector (D-CCR)

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Abstract

We devised and developed a novel directive projection screen for applications such as personal use, small group meeting, automotive pillar, and near-eye. This screen reflects and diffuses incident light at an angle $\Delta\theta_{view}$ around a direction deviated by θ_{view} from the direction of the projector. We realized the screen by employing a hollow cube corner retroreflector (CCR). The bottom surface of the CCR was tilted by $\theta_{view}/2$ to change the direction of the reflected light by θ_{view} from the retro-reflection direction. Furthermore three side surfaces of the CCR (D-CCR) were curved to diffuse the light within a designed angle ($\theta_{view}\pm\Delta\theta_{view}/2$). We simulated a D-CCR with θ_{view}=10° and $\Delta\theta_{view}$=16°, i.e., the viewing angle for a single D-CCR, 10°±8°, and fabricated a prototype. We verified closely the desired characteristics in which an optical gain of 16 was obtained.

Author Keywords

Cube-corner retroreflector; CCR; D-CCR; solid CCR; hollow CCR; retroreflector; directional screen; automotive pillar.

1. Introduction

Projection displays in small to large sizes with low to high luminance units are the most growing market. Nowadays small sizes are more attractive for personal use, small group meetings, automobile pillars, near-eye displays, wearable displays and entertainments.

Projection displays mainly consist of a projector with optical engine and a passive optical projection screen. In general a projection screen is a canvas cloth or a surface texture. A projection screen is evaluated by the reflection luminance, i.e., the gain (G) with respect to perfectly diffusing surface, and angular reflection characteristic. By definition a perfectly diffusing screen is a Lambertian screen, independent of the viewing angle, with a gain of 1.0 [1].

Variety of screens for front projection have been studied so far, such as matte white diffusive screens, pearl screens, silver screens, and retro screens. A matte screen is a Lambertian type [1]. These screens have wide viewing angles in which the reflection direction and light diffusion or the gain are approximately controlled.

In this study we intend (1) to design directional screen, (a) with narrow viewing angle, (b) with high gain for personal applications and (2) to preserve the luminous flux incident on the screen or to save the projector power consumption. In this paper, we report on the design of directional screen with controlled direction and light diffusion pattern (narrow or wide) that preserves the luminous flux reflected on the screen. We employ an array of novel micro-hollow cube corner (corner cube) retroreflectors (CCR) with three sides curved surface in which the bottom surface is a divergent curved surface (D-CCR). In this study we consider hollow D-CCR, however, the solid D-CCR (prismatic D-CCR; filled with optical transparent resin) can also be used whenever a wide numerical aperture is required [2]. We employ a hollow D-CCR to control the directivity, i.e., the viewing direction, and the viewing angle (light scattering cone) of the screen. The screen cell is a pair of D-CCRs (upper and lower positions), that is a rhombus shape (◆) and the screen is similar to rhombille tiling.

2. Projection Geometry

(a) Conventional Projection Screen

A conventional head up projection display schematically is shown in Fig.1(a). The projection is located at overhead position of the viewer. The real image is projected on a white matte screen; i.e., a perfectly light diffusing characteristic with a gain of G=1 (Lambertian luminance distribution). A viewer is assumed to be in front of the screen. As an example of high gain screen, a bead screen and its reflected luminance distribution is shown in Fig.1(b). A viewer can view a high luminance by moving along the zenith angle, θ, because the directionality of the screen is fixed by the size and the refractive index of the beads. In addition the gain of bead screens (G=2-2.8, half-gain angle about 50°-30°) are higher than that of the white matte screen (G=1) [3].

The luminance characteristics of the aforementioned screens can be summarized as shown in Fig.1(c). The characteristics are mathematical models. However, the characteristics of physical models are slightly rounded at the half-gain angles, i.e., where the gains decreases with the increase in the viewing angle, θ, especially near the half-gain angles.

(b) Novel Projection Geometry

A directive screen reflects the incident light ray toward the viewer as shown in Fig.2(a). The position of an overhead projector is fixed over the viewer's head. The projected image (i.e., the light) is deflected toward the viewer, in which the reflected light is deviated from the projection direction by an angle of θ_{view}. The reflected light is assumed to be scattered into an angle of $\Delta\theta_{view}$ as shown in Fig.2(b). For comparison a Lambertian characteristics is shown in the figure. Here by definition the gain is the ratio of the luminance of the novel screen and that of the Lambertian, when both screens have the same surface area and incident luminous flux.

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3. Directive Screen Concept

(a) Optical Characteristic of a Single CCR

The optical concept of directive screen is based on retro-reflection characteristic of a CCR (cube corner retro-reflector). A hollow CCR is an optical device with three plane surfaces as shown in Fig.3(a). The dihedral angles are 90° in an ordinary CCR where the planes have optical surface with relatively perpendicular surface normal vectors. An incident ray on a CCR, after having three reflections on the inner surfaces of the CCR is directed toward the incident ray with opposite direction [1,3-5]. The reflection order is shown in Fig.3(b). It should be noted that two coordinate systems are used in this paper, x,y,z system for CCR, and X,Y,Z system for screen analyses.

(b) Light Deflection and Diffusion

The z-plane surface divergence angle θ_d ($=\theta_{view}/2$) of an ordinary hollow CCR with both sides of flat surfaces results in a deflection of the reflected ray with deflection angle of θ_{view} ($=2\theta_d$). The retro-reflected ray is deviated from that of the incident angle by two times that of divergence angle θ_d. However, to diffuse the reflected light a curved surface is required. By choosing a geometrical shape such as portion of a sphere, the diffusion distribution can be shaped into a symmetrical reflection characteristic around the deflected centroid retro-reflected ray, i.e., $2\theta_d \pm \theta_s$ (in vertical direction) as shown a z-surface curved CCR in Fig.4. The center of the curved surface is the position of retro-reflected ray with deflection angle of θ_d. The scattering angle between the diverted curved surface normal (at curved surface center) and the tangent of curved surface along the curvature varies within $\theta_d \pm \theta_s/2$. The tangent angle at the edge of the curvature is $\theta_d + \theta_s/2$ and at the vertex of D-CCR is $\theta_d - \theta_s/2$. These are the tangent angles ($\pm\theta_s/2$) of the curvature with respect to the divergent surface (θ_d), when the cross section of D-CCR is observed from the left (or right) side.

(c) Single Divergent Curved Surface and Two Sided Curved Surfaces CCR

By changing the bottom surface of the D-CCR to a divergent curved surface in the previous section, the light was scattered within $\theta_{view} \pm \Delta\theta_{view}/2$. However, for scattering light in all directions we need to change the side surfaces of the CCR into curved surfaces. The same curvature as that of the bottom surface is applied to the side surfaces. The modified D-CCR is a combination of three dimensional curvatures in which an incident light is reflected on three surfaces leading to an increase of scattering of the incident light.

The theoretical studies of directional reflective hollow CCR lead to an optical structure with single divergent curved surface and two sided curved surface D-CCR shown in Fig.5. The centroid line of three spheres and its neighboring surfaces function as a novel optical device that forms the nearly omnidirectional reflective characteristics. The arrangement of three spherical surfaces results in reflected diffusion pattern. In our study, the light deviation is the result of divergent bottom sphere that its axis is diverted with respect to surface normal of two other spheres.

4. Experiment Results

(a) Prototyped D-CCR

A sheet of designed D-CCR array was fabricated. The size of sheet is about 100×100 mm^2. The sheet contains an array of screen cells. Each screen cell is a couple of confronted D-CCRs (upper and lower positions), in which the AH is 200 μm and the radius of curvature is 830 μm. The divergence angle for the curved z-surface is $\theta_d=5°$ and the curvature tangents are $\theta_s/2=\pm4°$. An incident light ray on D-CCR front surface ABC, reflects on both upper and lower D-CCRs, resulting in upward and downward reflections.

(b) Measurement System

A set up of a laser light source, an aperture sheet (opaque area transmission>80%), photographic camera, half mirror, and D-CCR sheet sample are shown in Fig.6. The laser light beam was transmitted through an aperture and the retro-reflected light is screened on the opaque part of the aperture sheet.

(c) Retro-reflected Light Pattern of Single Divergent Curved-Surface D-CCR Screen

The reflected light pattern from the prototyped D-CCR screen was pictured on the opaque area of the aperture sheet (light diffusing film) as shown in Fig.7(a). The retro-reflected light was pictured on Z-axis. The deflected light appeared at $(\theta_r,\phi_r)=(10°,90°)$ and $(10°,270°)$. Scattered light due to single divergent curved surface can be observed along $\phi=90°$ and 270°. The light scattering function of the curved surface is notable in the figure.

(d) Retro-reflected Light Pattern of Three Curved-Surface D-CCR Screen

Reflected light pattern from the single divergent curved surface and two curved side surfaces D-CCR screen was pictured on the opaque area of the aperture sheet (light diffusing film) as shown in Fig.7(b). The retro-reflected light pictured on Z-axis. The deflected light appeared at angles of $(\theta_r,\phi_r)=(10°,90°)$ and $(10°,270°)$, and it is scattered in all directions, i.e., $\phi=0°$, 90°, 180°, and 270° by the divergent surface and three curved surfaces.

The image of our directional screen is shown in Fig.8(a), and for comparison a Lambertian screen (white paper) is also shown in Fig.8(b). Since we intended to design a see through pillar for automobile, we curved our screen as shown in Fig.8(c). We can observe a high-reflection even in case of curved screen, similar to automobile pillar.

5. Conclusion

For the first time a directional screen with controlled direction and scattering pattern was devised and developed. We employed a modified hollow cube corner retroreflector to control the retro-reflection direction and scattering light cone. The projection screen was an array of three curved cylindrical surfaces CCR, i.e., D-CCR, in which one of the surfaces had off-axis center resulting in divergent surface for directing the retro-reflection.

We verified closely the desired characteristics in which an optical gain of 16 was obtained.

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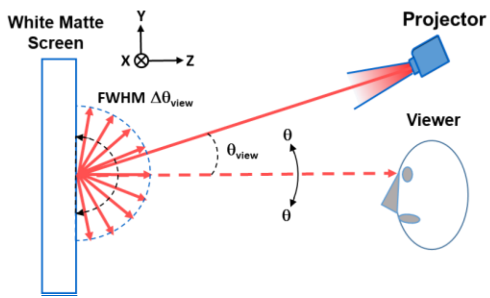

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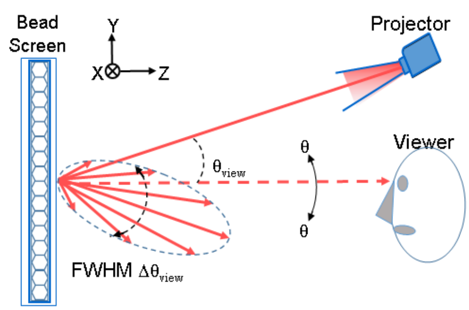

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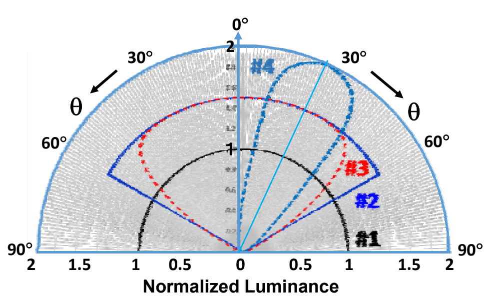
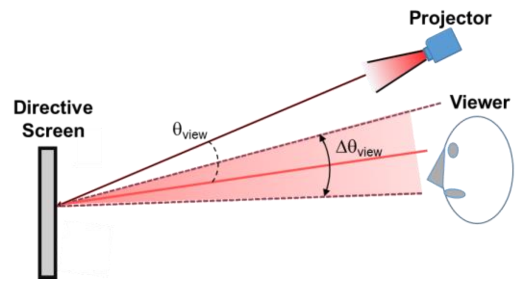
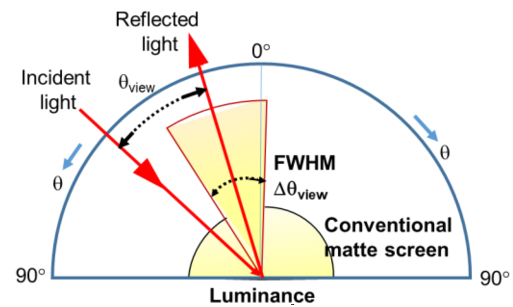


(c)

Figure 1. (a) Geometry of overhead projection with a white matte screen (Lambertian) with $(\Delta\theta_{view}, G)=(180°,1)$ and (b) a screen $(\Delta\theta_{view}, G)=(120°,1.5)$. (c) Comparison of the luminance distributions of a Lambertian (#1) with an ideal screen (#2), actual conventional screen (#3)、and a bead screen (#4) $(\Delta\theta_{view}, G)=(50°, 2)$.

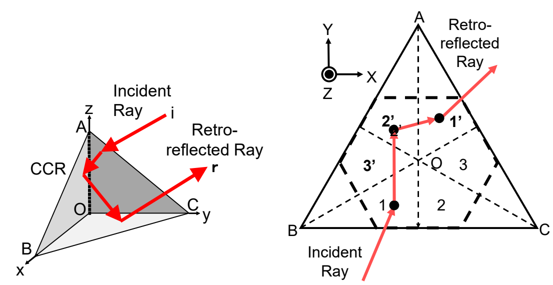


(a)



(b)

Figure 2. Novel projection geometry. (a) The concept is based on controlling the reflection direction, θ_{view}, and the light scattering angle, $\Delta\theta_{view}$. (b) The luminance of novel directive screen.



(a) (b)

Figure 3. (a) Cube corner retro-reflector. (b) Three-reflection areas are located within the hexagonal shape. Two-reflection zones are the triangles at corners (A, B, C). Two coordinate systems are used, (a) x,y,z system for CCR, and (b) X,Y,Z system for screen analyses.

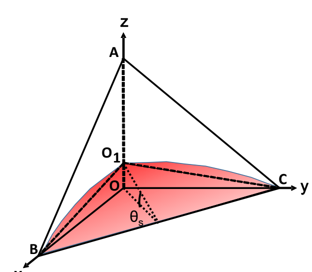
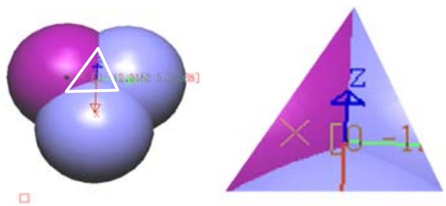


Figure 4. Cube corner retro-reflector with single curved surface and two flat plane surfaces.



(b) (b)

Figure 5. (a) Combination of three spheres, one with off-axis. (b) D-CCR with spherical surfaces.

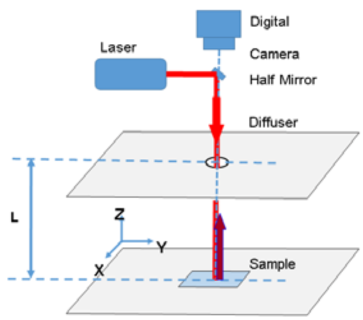
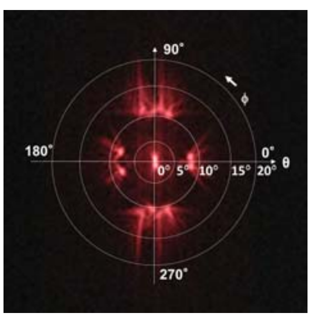
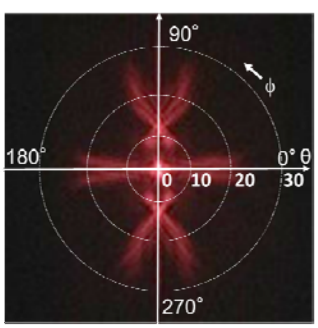


Figure 6. A set up for measuring the retro-reflected light of the D-CCR. A light diffusing sheet with low haze is used for screening the reflected light.



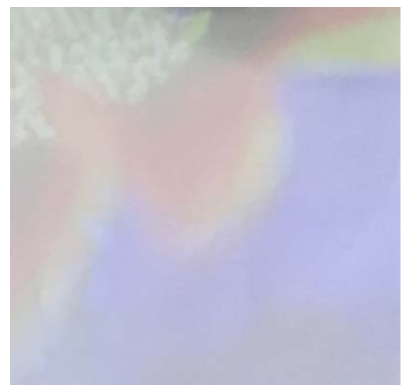
(a)



(b)

Figure 7. (a) Retro-reflected light pattern of the D-CCR screen with single divergent curved surface. (b) Retro-reflected light pattern of the D-CCR screen with single divergent curved surface and two sided curved surfaces.

(a)



(b)

(c)

Figure 8. A mini projector is used to project an image on four pieces of prototyped D-CCR screen each with a size of 100X100 mm^2. The D-CCR has a single divergent curved surface and two sides curved surfaces. Screen gain is 16, comparing the luminance values of the D-CCR and white paper screens. (a) D-CCR screen. (b) White paper as Lambertion screen for comparison. (c) Projected images on a curved D-CCR screen as an automobile pillar and a white paper screen for comparison.