A Novel Louver System for Increasing Daylight Usage in Buildings

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ABSTRACT: Advanced daylighting systems can be effective in increasing light levels in building spaces and reducing energy consumption due to electric lighting. However, a recurring issue found in most existing daylighting systems is the necessity of coupling the light-redirecting technology with a separate light shade to reduce glare risks. A different approach is proposed here, based on the use of a louver system which scatters incoming light onto a reflective ceiling, where it is redirected deep into the space. This type of system is effective for both diffuse daylight and direct sunlight without causing glare and without the need for a shading system. Annual simulations of workplane illuminance were conducted with Radiance using Tokyo weather data and a generic south-facing deep-plan office space. Glare was evaluated through testing of a physical prototype of the system. The new system was compared to a base case consisting of an unshaded window of equal area to the louver system. The results show that the novel louver system enables a significant decrease in electric lighting usage and outperforms the uncovered window, while adequately controlling direct sunlight to prevent glare.

Keywords: daylighting, louver, anidolic, building technology

1. INTRODUCTION

This paper introduces the design and operation of a new type of daylighting system. Daylighting systems are used to provide natural light to building spaces, reducing the need for electric lighting. Effective use of daylight has several positive benefits including lower energy bills, lower fossil fuel consumption for electricity generation, and increased work environment satisfaction for occupants [1].

The intention of this paper is to provide a proof-of-concept for the new daylighting system. The system described here is best suited for buildings with deep open-plan spaces, commonly found in office buildings. Both direct sunlight and diffuse skylight are directed into the room at an angle near horizontal, which allows the light to penetrate deeply. The system is designed to laterally diffuse incoming light in order to minimize glare resulting from direct sunlight. In this paper, the nature of the design problem is discussed and a description of the system is given. Test results from computer simulations, as well as a physical prototype, are also provided.

2. CONTEXT OF DESIGN

In general, daylighting systems can be divided into two categories: passive and active. Passive systems are fixed and contain no moving parts. Active systems contain moving parts, which are usually used to track the sun as it moves across the sky.

Since they have no moving parts, passive systems are generally less expensive and require less maintenance than active systems. However, these passive systems are typically only effective for a limited range of sun and sky conditions and some allow direct sun to pass through unimpeded at times, potentially causing glare. As a result, a separate shading system is often required, which leads to additional problems resulting from suboptimal control of the shading system [2].

Active systems are typically used to respond to the active nature of the sun. A common example is the venetian blind, whose slats can be adjusted, manually or automatically, in response to different insolation conditions. When automated, these systems are typically more expensive in both upfront and maintenance costs than their passive counterparts because they require rotating machinery, an accurate control system, and human monitoring [1]. Another limitation is that since most active systems are designed to use the sun’s radiation as input, their effectiveness is severely reduced under overcast conditions. In cloudy climates it may be difficult to justify the additional expense of a sun-tracking active system.

3. EXISTING SOLUTIONS

In broad terms, the goal of this design effort is to develop a passive system that performs well under all sky conditions, without causing glare. Two existing groups of technologies that informed the design of the new system were anidolic and louver daylighting systems.

3.1. Anidolic Systems

The search for a passive system that could redirect light deeply into a room, while also preventing direct sunlight from entering at a downwards angle, led to the science of non-imaging optics and a technology called the Compound Parabolic Collector (CPC). The field of non-imaging, or anidolic, optics was initially used in the development of solar energy collectors. The CPC was first used as a solar concentrator that could accept all light rays from a defined angular extent and concentrate them on a smaller area. The CPC, when used for daylighting applications, uses the same type of reflector profile, but light moves through it in the opposite direction. Light enters from all directions through a small inlet aperture and is aligned into a controlled angular range at the outlet [3].

Existing anidolic systems, based on the CPC, were found to have several major shortcomings when applied to an office building setting. First, for the system to be effective, it had to be excessively large, on the order of 1 to 2 m long and .5 to 1 m tall. This size reduces the ceiling height, makes using the space near the façade awkward, and complicates the construction of the façade. Second, when exposed to direct sun, the anidolic system is excessively bright and requires shading. In an open-plan office, blinds that are shut to control glare often remain shut for long periods of time [2]. This problem is only fully overcome by automating the shading system to eliminate the need for adjustments by the occupants.

3.2. Louver Systems

Reflective louvers form a second relevant group of daylighting systems. The main advantage of a louver system over a full-size anidolic system is that the louver systems are easier to integrate into a building and maintain because they are much less bulky and can be located between the panes of a double glazing.

Examples of existing louver systems include the Fish System and the LightLouver [1, 4]. These systems generally consist of a vertical array of identically-shaped curved slats, whose profile is defined so that daylight is redirected up onto the ceiling [1].

These existing systems, while useful, suffer from several drawbacks. For particular times of the day and year they can emit daylight at too high of an angle to allow the light to penetrate deeply, or worse, they can allow light to exit at a downward angle, potentially causing glare under direct sunlight. A second issue is the amount of light rejected by the outer part of the louver. When designed as passive systems, louvers often have difficulty admitting a wide range of incoming light directions while also effectively controlling the light output. Another drawback of these existing louver systems is that, although they may emit light at an angle near horizontal, light penetration depth is limited because they are designed to direct light onto a diffusing ceiling which scatters light uniformly in all directions.

4. PERFORMANCE OBJECTIVES

For the daylighting system to function effectively in a real office building setting, it will be subject to design constraints (visual comfort, space usage, etc.). As a result, a set of relevant reference performance objectives were developed based on the needs of the project sponsor, a commercial real estate development company located in Tokyo, Japan. Below are the key reference design requirements. The requirements reflect the desire for the system to minimize maintenance and space usage.

- Effectiveness: The system must respond well to both overcast and sunny conditions throughout the day and year.
- Visual Comfort: The system must avoid causing glary conditions inside the building space for all sky conditions.
- Passive Operation: The system should not require either human or computer-based adjustments to operate effectively.
- System Size: Real estate is usually very precious (and particularly expensive in Tokyo, the case study location), so the system size must be limited and must not interfere with the normal use of the office space, or the ability to see outside. The vertical extent of the proposed system is limited to the top .7 m of the façade. This distance includes .1 m for a horizontal mullion at the bottom of the daylighting unit, leaving .6 m of vertical height for the system itself.
- Ceiling Height: The floor to ceiling height is fixed at 2.8 m. A higher ceiling would improve lighting performance but maximizing rentable area takes precedence.
- Office Space: The space to be daylit is very deep at 12 m. The space is sidelit only.
- Urban Surroundings: Tokyo's urban landscape is full of tall, densely packed buildings. The result is obstructed sky views, especially the lower portions of the sky.

5. SYSTEM DESCRIPTION

A key insight gained during the review process of existing systems was that the principles of the CPC could be used to create a new louver system, which would improve on or eliminate the drawbacks of both the anidolic and louver systems described in Section 3. The resulting design is an original louver system that incorporates a CPC profile. The louvers, when combined with two other system elements, form an effective daylighting system which meets all of the requirements laid out in Section 4.

The system is comprised of two major subassemblies. The first of these subassemblies is a window unit installed at the top of the daylit façade. The other subassembly consists of reflective panels which cover the ceiling from the daylit façade to a distance of 6 m inboard (distance varies based on room size).

5.1. Window Unit

Figure 1 shows views of the window unit's cross-section. The unit contains two glass panes, similar to a standard double glazed window unit. Two different optical devices are located between the outer and inner glass panes. Both of these devices are sensitive to dust and scratching, so placing them inside the window unit provides protection and eliminates maintenance.

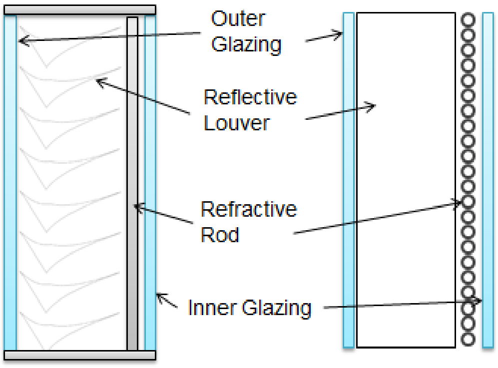

Figure 1: Window Unit Side View (Left) and Top View (Right)

The system is designed so as to ensure incoming light is redirected and diffused when entering the space so as to avoid glare risks. As a consequence, there is no view through the window unit itself, and the bottom of the unit should be no lower than approximately 2.1 m off the ground to allow for a view window on the rest of the façade.

5.2. Louver Assembly

The core of the system is a vertical array of reflective louvers which redirects incoming light in a controlled manner deep into the space. Figure 2 shows the relative positions of two louvers in the vertical array. The absolute size of the louver cross-section can be increased or decreased, but the ratio of the dimensions must remain the same for the device to function properly. The louvers have a constant cross-section in the direction normal to the page.

The output range for light emitted from the louvers is between 0° and 40° above horizontal, regardless of the incoming direction of the light. Figure 2 also shows how incoming rays at different positions and elevation angles will be redirected by the louvers. Notice that of all the ray paths traced in the image, none exits the louver channel at an angle less than 0° above horizontal.

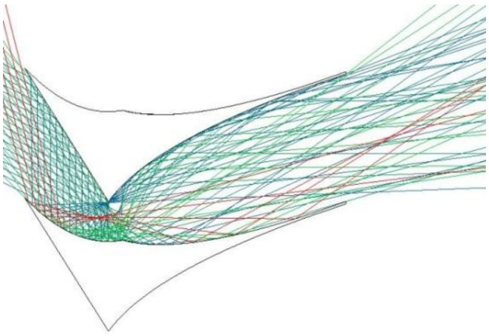

Figure 2: Ray Tracing through Louvers for Varying Incoming Elevation Angles

One important limitation to note is that some low angle light is rejected by the louvers. The cut off elevation angle, where the majority of incoming light rays are rejected, varies between 27° (for light normal to the façade in azimuth) to 0° (for light nearly parallel to the façade in azimuth). With this type of louver design, the tighter the output light's angular range, the more low angle light will be rejected at the inlet. For an urban setting such as Tokyo, the impact of losing light from near the horizon is less significant than it otherwise would be because the urban surroundings will often block the view to the bottom portion of the sky. All light that impinges on the louvers at an angle of 27° or greater will pass through the louver array successfully (minus absorption losses).

5.3. Refractive Rods

The louvers change the elevation of the incoming light but they do not significantly alter the light's azimuth angle. Without the inclusion of the refractive rods, under direct sun, the reflective ceiling will exhibit a bright streak located on a line between the occupant's eyes and the sun, similar in appearance to the sun's reflection off a moving body of water. During mock-up testing (discussed in Section 7) a maximum brightness of about 350,000 candelas/m^2 (or .02% of the luminance of the sun at mid-day) was observed on the ceiling when using the louvers without the refractive rods and this level of luminance was deemed to be too high for an office environment.

To mitigate glare concerns, a horizontal array of optically clear rods, made of either acrylic or glass, placed at the outlet of the louvers has the effect of spreading the incoming light in the azimuth direction, without affecting the light's elevation angle. Under direct sunlight conditions, the bright streak on the ceiling is replaced with a much larger area of lower brightness (see Figure 9). Diffusing direct sunlight in this manner helps prevent glare from being an issue. The total amount of light in the room is modestly reduced by adding the rods, but the glare protection they provide justifies their inclusion in the design. Figure 3 provides an illustration of how the rods affect light passing through them.

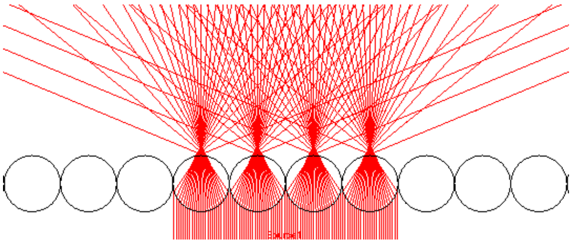

Figure 3: Ray Tracing through Transparent Rods Illustrating Their Ability to Mitigate Glare Resulting from Collimated Sunlight

5.4. Reflective Ceiling

The final element of the proposed daylighting system is the reflective ceiling. The purpose of the reflective ceiling is to redirect light emitted by the window unit deeper into the space. To limit glare and distracting mirrored reflections on the ceiling, the reflective surface has bumpy texture, which helps to scatter the light without eliminating its directionality.

If the surface of the ceiling had a typical matte or diffuse finish then most of the light exiting the window unit would hit the ceiling near the front of the room and be scattered onto the workplane immediately below. With a diffuse surface, impinging light is scattered in all directions evenly so only a small portion would be reflected off the ceiling deeply into the space. This is true even of light that exits the louvers near horizontal. A diffuse ceiling wastes much of the benefit of the louvers, because the ceiling cannot take advantage of the fact that the light impinges on it at a shallow angle.

Since increasing the distance from the louvers to the ceiling is not an option due to economic constraints, another solution to push light deeper was sought. Using a ceiling with a specular, rather than a diffuse, surface makes the overall system much more effective. Light hitting the ceiling at a shallow angle bounces off at a shallow angle. This means that all the light is directed deeper into the space at a favorable angle, rather than being diffusely scattered.

The refractive rods and bumpy ceiling texture prevent the specular reflection off the ceiling from causing glare by reducing the peak brightness associated with direct sunlight. This method of diffusing incoming light should provide protection from thermal discomfort as well, since the building occupants are not exposed to direct sunlight. With regard to solar gains, this system will allow a heat input similar to the standard glazed curtain wall with interior blinds. Its overall impact on building loads will also be limited since the daylighting window unit only covers a fourth of the full façade height.

For a daylit zone extending 12 m from the façade, the recommended length for the reflective ceiling is 6 m, but this could be reduced to 4 m with a relatively small impact on performance if cost or other considerations limit the allowable length. The rest of the ceiling beyond the end of the reflective section could use a standard acoustical tile layout.

6. SIMULATION RESULTS

6.1. Model Description

To give a quantitative idea of how the system performs, the figures in Section 6.2 show illuminance results for a generic south-facing building space with the full daylighting system compared to the same space with an unshaded window and a diffuse white ceiling for two different representative sky conditions. The unshaded window is a common point of comparison for daylighting systems under test and is one of two standard reference cases defined by the International Energy Agency's Solar Heating and Cooling Task 21 [1]. A generic unshaded window provides a simple reference case that is easily modelled and understood.

The lighting simulation program Radiance was used to run the simulations [5]. To conduct annual simulations in a reasonable amount of time, the daylight coefficient method employing the rtcontrib Radiance program was utilized [6].

The façade below 2.2 m from the floor is modelled as an opaque wall for both cases to isolate the effects of the daylighting system. The base case leaves the top .6 m of the glazed façade uncovered, while the system case includes the full daylighting system. The building space is located using Tokyo's latitude and longitude and its south façade has an unobstructed view of the sky. Workplane illuminance values are measured along the centerline of the room moving away from the south façade. All walls, other than the top of the south façade, are completely opaque. The Tokyo weather file available from the Energy Plus website was used as the source for direct normal and diffuse horizontal irradiance values. Additional model details are provided in Figure 4 and Table 1.

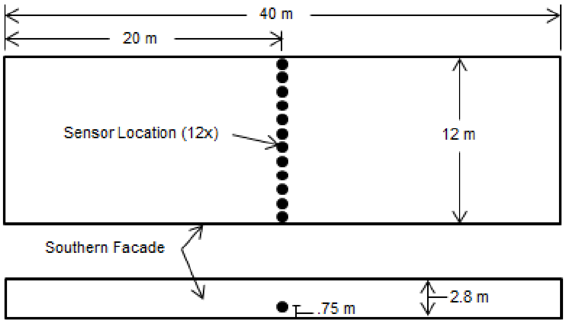

Figure 4: Plan (Top) and Section (Bottom) Views of Model Space with Dimensions

Table 1: Radiance Model Parameters

Floor Reflectance	0.20
Wall Reflectance	0.60
Standard Ceiling Reflectance / Specularity	0.80 / 0.00
Reflective Ceiling Reflectance / Specularity	0.88 / 0.95
Louver Reflectance	0.92
Rod Transmittance / Index of Refraction	0.92 / 1.50
Window Transmittance (for Double Pane)	0.74

6.2. System Performance

Under sunny conditions, the louver system outperforms the unshaded window base case, as shown in Figure 5. The louver system provides significantly more light than the base case for depths of 2.5 m or greater. Also, the louver system avoids the extremely high peak illuminance seen in the base case resulting from direct sunlight transmission. In practice, the illuminance peak from direct sun would likely cause the occupants to partially or fully close the blinds, reducing the room illuminance contribution from daylight. For reference, the minimum recommended illumination level for office work is typically between 300 and 700 lux.

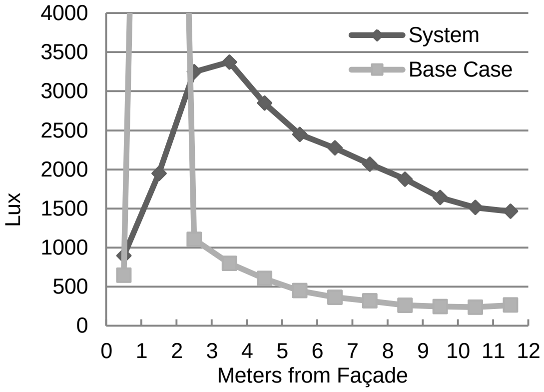

*Figure 5: Sunny Case: March 24, 11:30am (Direct Normal Irradiance: 955 W/ m^2, Diffuse Horizontal Irradiance: 97 W/ m^2) *Base Case at 1.5 m is 20,413 lux*

Under totally overcast conditions, the overall illuminance levels for both cases are much lower than for sunny conditions. Despite the reduction in absolute illuminance, the proposed louver system still outperforms the uncovered window at distances of 4.5 m or greater from the façade, as shown in Figure 6. The system also increases the uniformity of light levels in the room.

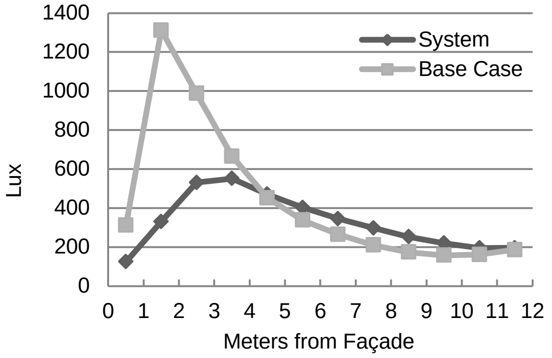

Figure 6: Overcast Case: March 25, 11:30am (Direct Normal Irradiance: 1 W/ m^2, Diffuse Horizontal Irradiance: 260 W/ m^2)

For situations where there is significant sky obstruction near the horizon due to the daylit building's surroundings, the louver system performs even better relative to the uncovered window case. This is because the uncovered window relies primarily on light from near the horizon to illuminate the deep parts of the space, unlike the louver system. Also, for the open window case to be a viable option it would require some type of movable shading system to shield the office space from direct sunlight, a drawback the louver system does not suffer from.

To give a more complete impression of the system's performance on an annual basis, Figure 7 provides the median annual workplane illuminance values for selected hours of the workday. The louver system consistently provides more light than the base case at distances greater than 3.5 m from the façade.

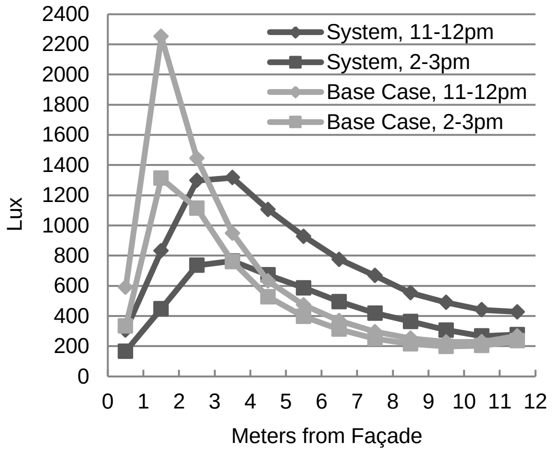

Figure 7: Median Annual Workplane Illuminance for Daylighting System and Base Case

Figure 8 shows the annual percentage of working hours where the workplane illuminance exceeds 300 lux.

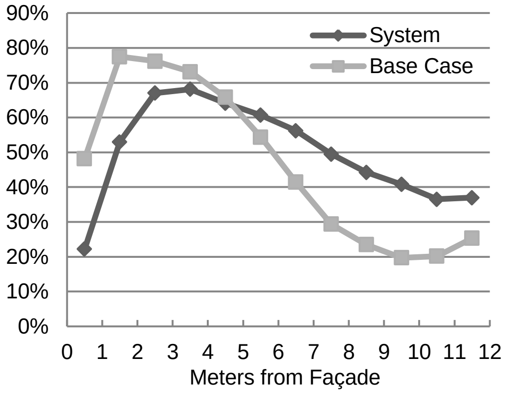

Figure 8: Percent of Working Hours (8am-7pm) with Workplane Illuminance Greater than 300 Lux

In addition to outperforming the uncovered window base case, the new system appears to also outperform many existing passive daylighting systems. Aizlewood conducted a study of four different advanced passive daylighting systems: a light shelf, Okasolar louvers, a prismatic glazing, and a prismatic film [7]. All of these systems were found to reduce workplane illuminance compared to an unshaded window for overcast conditions. Under the variety of sunny conditions found over the course of the day and year, no system was able to consistently provide increased workplane illumination in the rear part of the room either. Furthermore, it was determined that all of the tested systems, other than the prismatic film, required a separate shading system in order to limit glare. Although these results suggest that the new system may provide superior performance in terms of amount of illumination, depth of illumination, and glare control, making a conclusive judgement of the relative effects of two different daylighting systems requires that both be tested under identical conditions.

7. PHYSICAL PROTOTYPE

A physical prototype of the daylighting system was built to test for glare problems as well as to obtain a qualitative understanding of aesthetics of the system. The dimensions of the completed louver unit were .27 m wide and .15 m tall, not including the frame. The prototype used eight louvers, whereas the real system would use approximately 30 to fill the .6 m facade height allowed.

Glare was evaluated using point luminance readings as well as qualitative assessments and was not found to be a significant concern. At its brightest, the reflective ceiling does not cause visual discomfort, provided the ceiling is not in the center of the field of view. The ceiling can cause slight visual discomfort if in the center of the field of view. These conclusions will be refined with additional testing. The addition of the refractive rods to the system reduces the peak luminance of the ceiling while increasing the ceiling's average luminance, as shown in Figure 9. The data presented in Figure 9 was recorded on a clear November day in Cambridge, Massachusetts near 10:45am at a constant distance of 3.5 m from the window unit. The prototype was aligned so that the azimuth angle of the incoming direct sunlight was 90°.

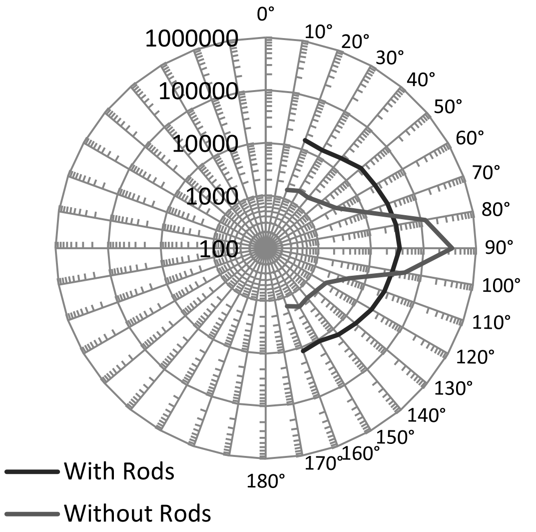

Figure 9: Prototype Ceiling Maximum Luminance (cd/m^2) as a Function of Azimuth Angle to Façade

Figure 10 illustrates how adding the refractive rods reduces the peak luminance of the ceiling.

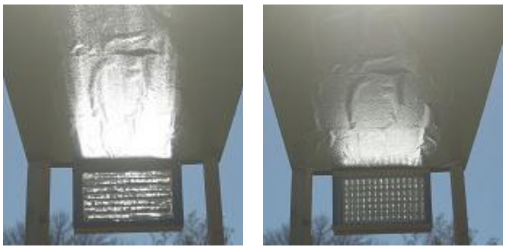

Figure 10: Peak Brightness of Prototype Under Direct Sun Without Rods (Left) and With Rods (Right)

Figure 11 shows a picture of a full scale mockup tested in Tokyo, Japan. Analysis of data from this more sophisticated mockup is in progress, but the results are well aligned with those of the initial mockup.

Figure 11: Full Scale Mockup Installed in Office Building Setting

8. CONCLUSION

The new daylighting system proposed here has the potential to bridge the gap between automated systems that are expensive and maintenance-intensive and passive systems which are often ineffective and cause glare. The system is simple, passive, and maintenance free. It is also well suited for both sunny and cloudy conditions without requiring any reconfiguration.

The feasibility and performance of the system has been evaluated through the use of computer simulations and a physical prototype. The results are very encouraging, for both illuminance levels and visual comfort. Development of this technology is continuing and the completed system is planned to be permanently installed in a new Tokyo office building in 2012.

9. ACKNOWLEDGEMENTS

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