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Concept of Solar Tower for Daylighting in Multi-Floor Buildings

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Recently, it has been found that more consideration has been given to the interaction between buildings, energy, and the environment. As buildings are the main source of energy use and greenhouse gas emissions, sunlight, which is one of the renewable energy sources, is provided in the interior to save electric lighting power consumption and improve indoor environments. Conventional daylighting systems have their difficulties in making a large-scale system to illuminate the entire building. We propose a daylighting system, which delivers sunlight to each floor of the building. Sunlight is captured, guided, and distributed through the heliostats, mirror light pipe, and light guide, respectively. The light guide is made of prismatic optical lighting film and multi-layer optical film for achieving uniform illumination in the interior. The proposed system is advantageous because it can be made according to the building structure and the size. Finally, extensive acceptance of the system can reduce electric lighting power consumption in buildings, which would help to reduce carbon dioxide emissions.

Keywords: Solar Energy, Sustainable Building, Daylighting, Heliostat, Light Pipe.

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1. INTRODUCTION

Current directions toward green buildings possess energy efficiency, conversion of sources, renewable energy, and healthy environment, which includes light and air quality. One of the principles of these buildings is to utilize natural light at all day to illuminate the interior. It is clear throughout history that lighting has been an important element in the architectural designing. Daylighting has been recognized a major source to improve indoor environments. It is essential in buildings because it has various benefits such as light quality, energy efficiency, psychological effect, and healthy environment.

In South Korea, 43% of CO_2 emissions were produced from coal, 37% from oil, and 20% from Gas, and it was approached to 515.5 million tonnes of CO_2 in 2009.[1] It has been estimated that 46% and 71% of total energy is consumed in buildings of South Korea and U.S., respectively.[2] Commercial energy consumption in terms of electric lighting approaches to 40–50%, and industrial energy consumption approaches to 10–20%.[3] In sustainable buildings, energy saving is one of the main targets. Solar energy is one of the main sources of electricity production, and it can be used for daylighting. A reduction in energy consumption can be achieved by decreasing the use of artificial light in buildings. Daylight building is estimated to reduce lighting energy consumption by 50–80%.[4] In commercial buildings, electric lighting consumption can be reduced by 50–70% using daylight designing techniques with efficient artificial lighting controls.[5] The daylighting systems have been recognized to displace lighting energy consumption while providing very high quality illumination.

It has been estimated that natural light provides more light for less heat than artificial light. For example, it was monitored that a tungsten light source produces 5–14 times more heat than daylight.[6] To remove the heat, which is produced from each 100 watts of electric lighting, 20–50 watts are required.[3] In this case, we have to pay for both the cost to remove unwanted heat and the electric lighting. Approximately one watt of heat gain is attained from 100 lumens of illumination with sunlight.[3]

Since light from the windows decreases very rapidly, and interior areas may not have sun exposure. As a result, the illumination is not consistent and some areas may remain dark. It has been estimated that about 70% of the room requires supplementary electric light, irrespective of the outdoor lighting conditions.[7,8] There should be some other source to provide sunlight for remaining areas to reduce electric lighting energy consumption. Therefore, we shall deliver daylight in those areas of the building through the proposed daylighting system. It guarantees to deliver sunlight deep into the core of the multi-floor buildings.

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Numerous demonstrations have been presented to capture, guide, transport, and conversion of solar radiations such as solar concentrators, reflectors and lenses, light pipe and optical fiber, and solar thermal and solar photovoltaic, respectively.[9] Four main sunlight transport methods, namely, beam/lens system,[10] mirror light pipe (MLP),[11] prismatic light pipe (PLP),[12] and optical fiber,[7] have been examined. In the beam/lens method, the light through a collimating device is transported by arrangement of lenses and mirrors. In the MLP method, the sunlight is captured through lenses and reflectors and inserted into the light pipe and then light is transported and reflected from the inner surface of the pipe. PLP is made of prismatic dielectric surface in which light is trapped inside the light guide by total internal reflection. For daylighting, optical fiber is known as a good light transmission media, but it is costly. Thus, light pipe is preferred to make the system cost-effective.

To follow the need of the market and energy codes, there should be simple methods in the daylighting system. Several concepts regarding daylighting systems have been demonstrated using optical fibers and light pipes,[13–22] and most of the designs have a large number of tracking reflectors and lenses, and, thus, require an adequate area in which to be installed. In most of the cases, the building was illuminated by installing daylighting system separately for each floor. However, it increases the cost of the system. In order for daylighting system to be implemented on a large-scale, the cost of the system needs to be substantially reduced. It is better for the system to install the light collecting module on the roof of the building to use available free portion of the building. Therefore, we installed the sunlight collecting system on the roof of the building.

Daylight levels inside a lecture room were analyzed using a light pipe and fiber-optic solar dish through simulation.[20] Sunlight was entered into the light pipe through a transparent dome cover. A solar dish tracked the sun all day to capture direct sunlight. It was demonstrated that more daylight can be harvested through the tracking-dish concentrator for solar altitudes of less than 50 degrees, and a greater number of lumens was available for the light pipe at a higher solar altitude. Furthermore, it was found that tracking-dish concentrator gave high illuminance uniformity at different solar altitudes than that of the light tube.

A lightwell design was demonstrated to bring daylight to each floor of the multi-story building.[21] The lightwell, which acted similar to light pipe, had a width of 100 mm, length of 800 mm, and height of 800 mm. The simulation results were achieved for six floor building. It was found that the top three floors received sufficient daylight showing daylight factors (DFs) greater than 2%. The lower three floors received DFs lower than the recommended value of 2%.

The main purpose of this study is to deliver uniform daylight in the interior (e.g., a multi-floor building's interior) through MLP. For this purpose, heliostats are preferred to capture high intensity sunlight and make the system cost-effective. Uniform light is distributed in the interior through a light guide. Flow chart of the daylighting system is shown in Figure 1. In future, a hybrid system of combining sunlight and light emitting diode (LED) light will be explored where LEDs will be mounted inside the light guide for achieving uniform illumination and decreasing the light changing effect. This research will improve the efficiency of the light pipe-based daylighting system.

The remainder of the paper is organized in the following manner. Section 2 describes the architecture of the daylighting system. Performance parameters are discussed in Section 3. The detailed description of the light distribution in the interior is discussed in Section 4. The complete study, involving the simulation, the implementation of the system, and the evaluation of the results are presented in

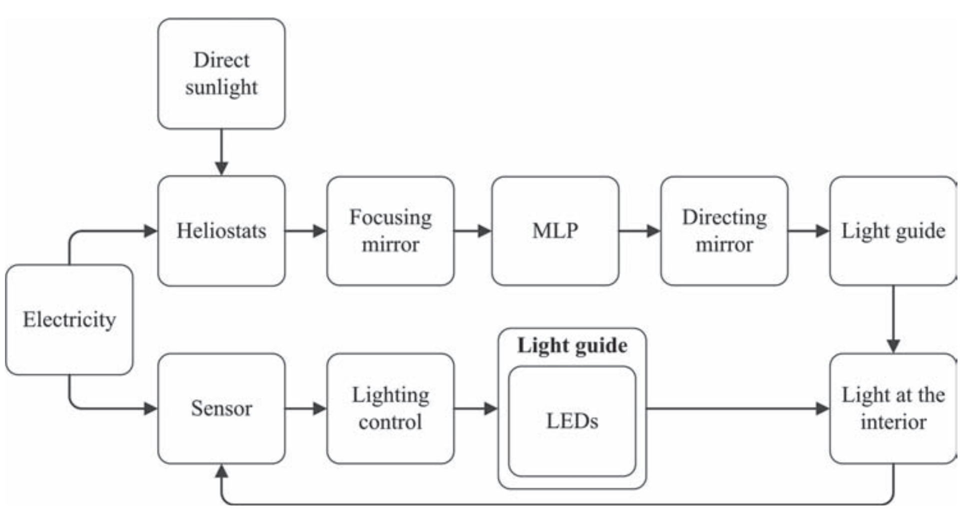

Fig. 1. Flow chart of the hybrid daylighting system.

Section 5. Finally, brief concluding remarks and future work are included in Section 6.

2. BASIC CONCEPT OF THE PROPOSED DAYLIGHTING SYSTEM

The main objective of the proposed approach is to accelerate and facilitate the integration of the daylighting system in office buildings that are the main source of world energy consumption. The daylighting system should collect high-intensity sunlight from the outdoor and distribute it throughout the building. Most of the concentrators have issues about perfect alignment, high concentration ratio, and rapid manufacturing. In the fiber-based daylighting systems, sunlight is delivered in the interior through the bundle of optical fibers. However, high concentration, which needs very high quality optics and a precise sun tracking system to focus sunlight into the optical fibers, is essential for these methods.

We propose a cost-effective approach for the daylighting system to achieve high-intensity sunlight. Sunlight was captured through heliostats of circular plane mirrors that were arranged in circular arcs around the MLP, as shown in Figure 2. Each heliostat directed sunlight toward the focusing mirror, which was installed upstream of the MLP. The Focusing mirror inserted light into the MLP and then light was transported through the MLP. To deliver the light at each floor, a directing mirror was used to insert the light into the light guide, as depicted in Figure 3. Sunlight is distributed in the interior through the light guide. In future, we shall add solar cells at the end of the MLP to generate electricity.

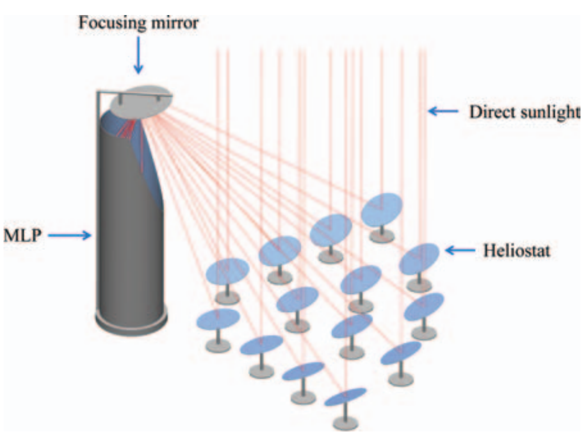

Fig. 2. Physical layout of a typical ray-tracing simulation for the daylighting system in which light directing, focusing, and guiding through the heliostats, focusing mirror, and MLP is shown, respectively.

3. PERFORMANCE PARAMETERS

The heliostats were arranged into circular arcs of radius 1.5 m, 2.5 m, 3.5 m, and 4.5 m, as shown in Figure 4. We used thirteen heliostats to illuminate five floors, and each floor had an area of 50 m^2. The heliostat had a diameter of 0.7 m. In this study, heliostats were arranged on one side of the MLP. Heliostats can be arranged on all sides around the MLP by changing parameters and design. It was supposed that each heliostat had two-axis sun tracking system to track the sun all the daytime. The focusing mirror had a diameter of 1 m, and the distance between the focusing mirror and the MLP was 0.5 m. The Focusing mirror made an angle of 10.12 degrees with the ground axis. The MLP was designed cylindrically to achieve uniform light. Maximum sunlight was directed into the MLP by

$$D_t = D_m \tag{1}$$

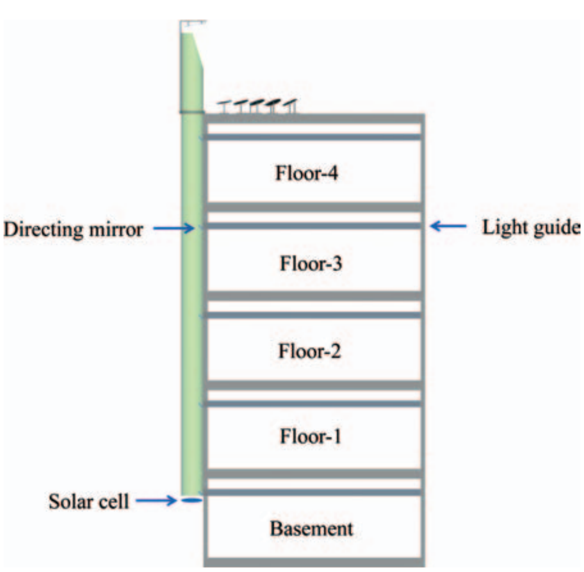

Fig. 3. Component layout of the daylighting system.

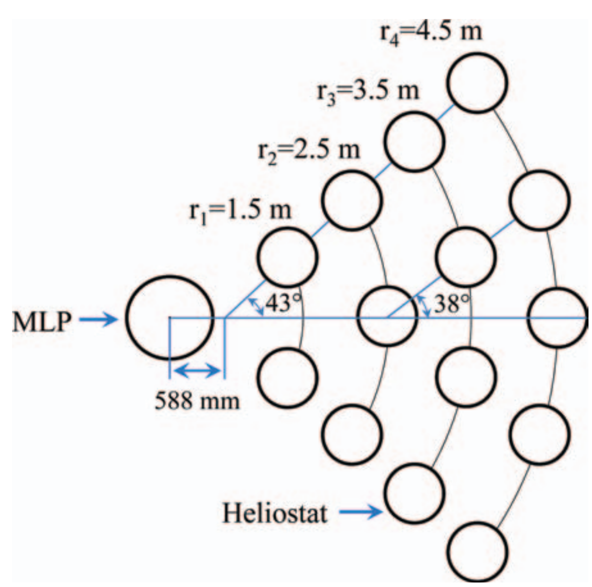

Fig. 4. Schematic showing the parameters of the light collecting system.

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where D_t is the diameter of the MLP and D_m is the diameter of the focusing mirror. The MLP had a diameter of 1 m and a length of 19.9 m. The optical transmittance of the MLP can be approximated as[23]

$$T = R^{l\tan\theta/d_{\text{eff}}} \quad (2)$$

$$d_{\text{eff}} = \pi d/4 \quad (3)$$

where R is the reflectivity of the pipe, l is the length of the pipe, θ is the angle of incidence of the illuminating radiation with respect to the axis of the MLP, and d_{eff} is the effective diameter. We considered a building in which the MLP was installed on left side. It can also be installed in the center of the building to illuminate the interior of the building. The building had five floors, including basement. The number of floors to illuminate can be increased by increasing heliostats or by changing the size of the MLP and the heliostats. Therefore, the required design can be easily created to satisfy the required illumination for a specific area.

4. DISTRIBUTION OF SUNLIGHT IN THE INTERIOR

Recently, numerous approaches have been presented to achieve uniform illumination from light sources.[7] In solid-state lighting, this issue has gained critical importance.

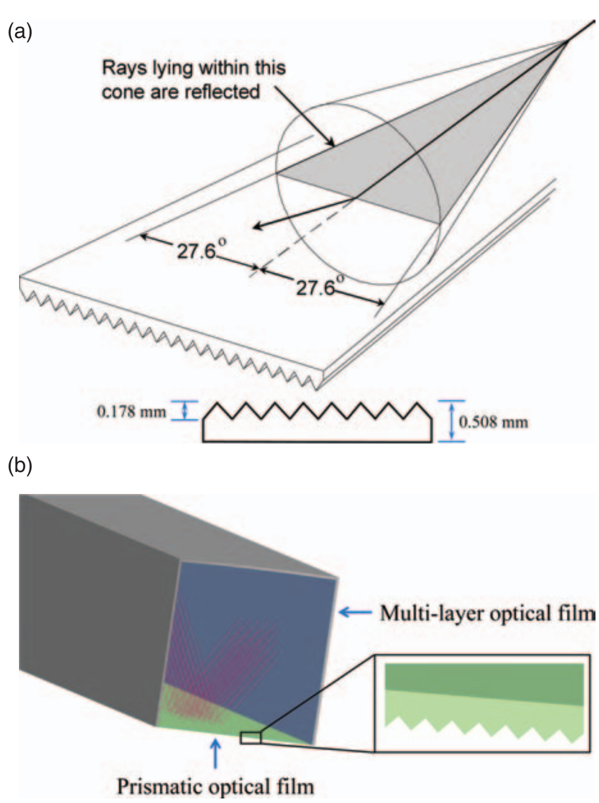

Fig. 5. Illustrating (a) optical lighting film and (b) prismatic light guide to distribute light in the interior.

Table I. Average illuminance at different times of the day and calculated flux for the heliostat.

Time	Solar altitude (°)	Outdoor illuminance (lx)	Flux (lm) for heliostat
6 AM	8	20000	9800
7 AM	19	40000	19600
8 AM	31	60000	29400
9 AM	43	80000	39200
10 AM	54	100000	49000
11 AM	65	105000	51450
12 PM	74	110000	53900

Similarly, uniform illumination is mandatory in daylighting. To spread the light from the MLP, which had a high beam of light, prismatic light guide was used. The light guide was made of prismatic optical lighting film, which had a thickness of 0.508 mm with prisms on one side, and multilayer optical film, as shown in Figure 5.[24] Optical lighting film had a transmittance of 99% and a reflection of 99%,[24] and multilayer optical film had a reflection of 97%.[25] The light guide had a width of 304.8 mm and a depth of 304.8 mm. The light guide gave uniform illumination with better illumination quality, and it transmitted

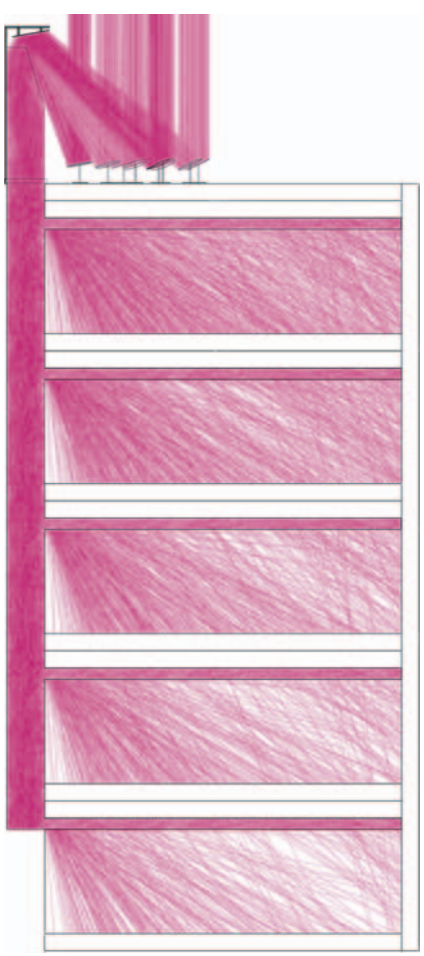

Fig. 6. Schematic showing how light was distributed through the light guide, including ray-tracing.

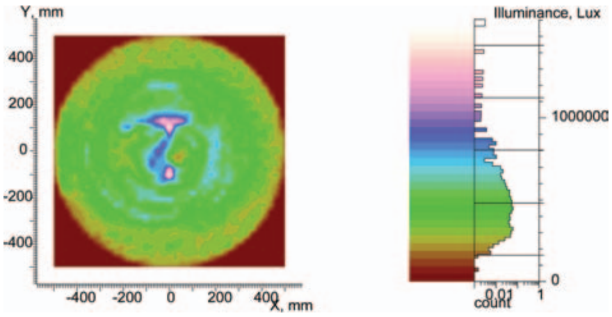

Fig. 7. Uniform illumination inside the MLP.

light at a long distance.[26] Thus, the system was capable to capture high intensity sunlight and to illuminate core region of the building through the light guide.

In South Korea, the minimum floor-to-floor height is 3 m with a ceiling height of 2.4 m.[27] In the U.S. and Asia, the floor-to-floor height of typically office buildings is between 4 m to 4.2 m.[28] In this system, we used a standard 4 m floor-to-floor height and a ceiling height of 2.74 m (Fig. 3).

5. SIMULATION AND RESULTS

In this research, we present a simulation study of the proposed approach. LightTools®, which is a well-known, optical-simulation tool,[7] was used to design the optical and mechanical components of the daylighting system, analyze the efficiency of the system, which includes light losses due to mechanical and optical components and illumination uniformity, and estimate the illuminance levels in the interior. Almost all losses (i.e., due to reflection and the transmittance of materials) were considered in the simulation to analyze the performance of the system efficiently. In the simulation, a real time environment was generated by designing each part and considering each loss. The source, receiver, reflectors, prismatic optical film, and other hardware modules were designed in the software. For daylight, lumens was calculated to simulate the entire optical design for indoor by[29]

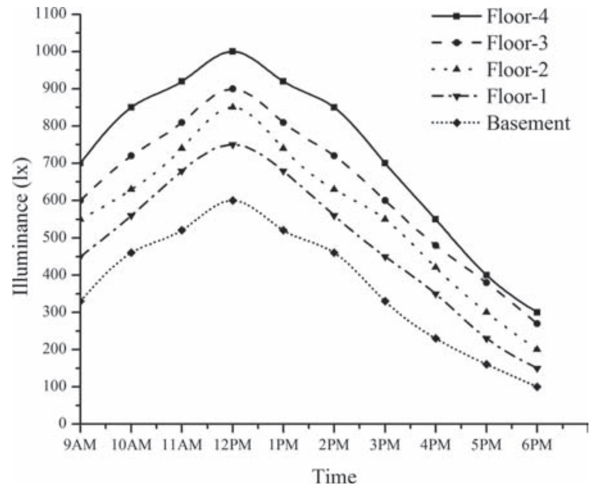

Fig. 9. Daylight average illuminance in the room at different times of the day.

$$E = \frac{dF}{dS} \tag{4}$$

where E is the measured illuminance, d_F is the input luminous flux in lumens, and d_S is the area of the concentrator. We can calculate the simulated input flux from the measured illuminance (Eq. (4)). Measured illuminance at different daytimes and calculated flux is mentioned in Table I.

The site of the application (multi-floor building) was located at 127° longitude and 37.5° latitude. In Figure 6, we show an example of ray-tracing for the proposed daylighting system in which direct rays were inserted on the

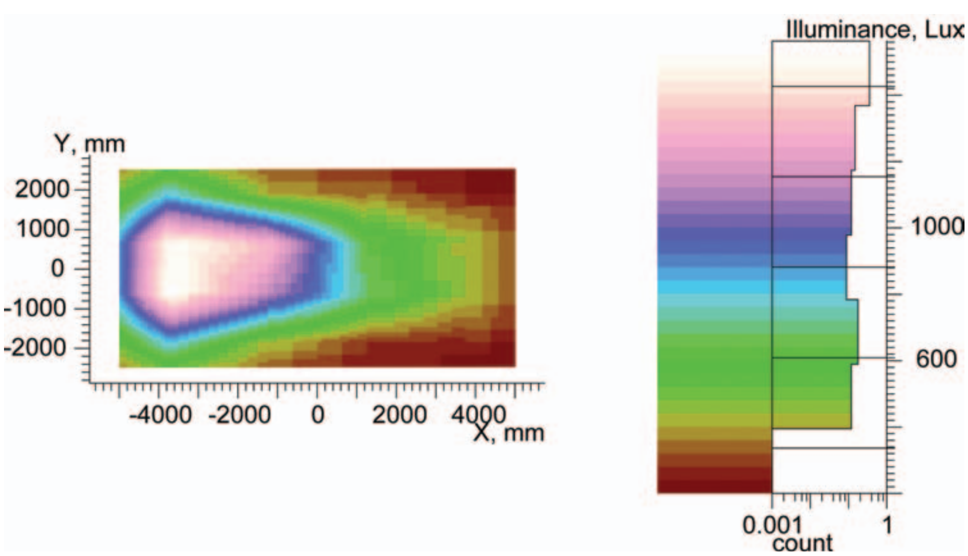

Fig. 8. Daylight illuminance distribution in the interior.

system. For daylight simulation, the system was illuminated by inserting average illuminance of 100 Klx, and the illuminance was measured inside the MLP. As evident from Figure 7, uniform illumination was achieved in the MLP. In the interior, the illuminance was measured at 2 m below the roof of the room (work plane). The Illuminance distribution on the work plane at 12 PM for the floor-4 was measured, and an average illuminance of 850 lx was achieved, as shown in Figure 8. Various experiments were conducted to measure illuminance levels in the building at different times of the day, as shown in Figure 9. The minimum requirement for office illumination is to achieve an average illuminance of more than 500 lx.[30] We have achieved the required minimum average illuminance value for the office building.

6. CONCLUSIONS

We have demonstrated a cost-effective daylighting system for multi-floor office buildings to save electric lighting energy consumption. A high intensity of sunlight was attained through heliostats, and uniform light was achieved inside the MLP to distribute light equally to each floor. Prismatic light guide was used to distribute sunlight in the interior uniformly. Thus, it is possible to deliver sunlight to each floor of the building. Previously, it was difficult to capture high intensity sunlight for illuminating the entire building. We solved the concentration problem by using heliostats to capture highly concentrated sunlight. The proposed system has been highly accepted due to the simplicity of its design, the ease in manageability, the applicability of rapid manufacturing, the cost-effectiveness, and because it is widely expandable to produce large-scale systems.

The research is in the early stages of development and implementation of the system, and it is currently underway to verify the cost effectiveness and its energy-saving benefits. In future, we shall guide sunlight into the light guide to transmit it at long distance by designing the directing mirror in an efficient way. Solar cell will be placed at the end side of the MLP to produce electricity, which can be used for sun-tracking and artificial light when daylight is not available. This research can be further extended to different solar energy applications (e.g., solar thermal energy and concentrated photovoltaic).

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