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# Development of Daylighting System with Modified Light Pipe for Longer Transmission Distance and Higher Illuminance

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### *Abstract*

*In this research, we present a natural lighting system with transmission distance of 30m and lighting efficiency of 35% (30m standard) for operating hours of 7h/day (based on clear sky). The system is composed of parabolic reflective mirror and modified light pipe that can secure more than 88% of light concentration efficiency. The light loss rate of newly designed light pipe transmission system is demonstrated to 0.8 %/m in the straight-line part and 2%/m in the curved part. Modified light pipe daylighting system shows better performance over fiber optic daylighting system in terms of transmission distance (1.5 times longer) and illuminance (3.05 times higher).*

**Keywords:** *Daylighting systems, Parabolic reflector, Light pipe transmission, Solar energy.*

## 1. Introduction

Around the world currently, about 56% of the population lives in urban areas according to UN estimates. People living in urban areas spend most of their daylight hours under artificial light and are susceptible to detrimental effects. Some studies indicate that artificial light is induced aggravating depression, aggression, eye strain, reduced muscle strength, obesity, and diabetes [1]. So, daylight plays an important role in improving health and it is also important in the field of renewable energy in terms of reducing the use of electricity. The

U.S. Energy Information Administration (EIA) estimates that in 2020, about 404 billion kilowatt-hours (kWh) of electricity was used for lighting by the residential sector and the commercial sector in the United States. This was about 10% of total U.S. electricity consumption, and electricity demand is growing by 0.7% per year in buildings in the U.S. [2]. In Europe, about 40% of the total electricity is used for indoor lighting in buildings.

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To improve the working environment and solve energy issues, sustainable buildings are introduced. One of the principles of these buildings is to illuminate the building by daylight instead of artificial light at all times of the day to reduce the overall energy consumption. Buildings in which efficient daylighting methods are applied can reduce electric lighting energy consumption by 50%–80% [3]. However, areas not adjacent to sunlight or metro and mine areas often find it difficult to bring sunlight into space illumination, which is the reason why daylighting systems are emitted thriving in recent times.

Throughout the last two decades, many daylighting systems that concentrate and transport daylighting into the interior were developed. Light pipe technology has commercially exploited over the past fifteen years. Recently, light pipe systems are commercially available in the market as Solatube, Skydome, and etc. Because the principle of light pipe system is based on reflection, the use of elbow or bend will result in light loss [4], each elbow may cause 8% loss of light, therefore for light pipe systems, the transmission distance is limited to less than 5 meters. Optical fiber daylighting system (OFDS) captures highly concentrated direct component of sun light and focuses it into optical fibers and distributes the visible part of it into interior of buildings. Himawari system developed by a Japanese company is the first commercial daylighting system based on quartz optical fiber as a light transmission medium [5]. ECHY–optical fiber system using the same principle of Himawari's released the first commercial product in 2018 [6]. Although optical fiber daylighting technologies have the ability to bring sunlight deep into buildings, however, it has durability issue. Since silica optical fibers (SOFs) are expensive and difficult for bending, plastic optical fibers (POFs) are preferred for actual implementation. POFs experience irreversible thermal damage if the temperature of concentrated light is above 70°C, therefore, extra thermal protection should be done for OFD systems [7]. Even if OFDS has an advantage of longer transmission distance, when the natural light is focused into fibers, it loses some of its spectrums due to material characteristics of silica or PMMA. On the other hand, the conventional lightpipe daylighting system has a disadvantage of short transmission distance, whereas the light spectrum is fully transmitted. In this paper, we introduce modified-light pipe (light tube) based daylighting system which overcomes the previous short distance transmission problem. The system allows light transmission deep inside up to 30m, and the modified light tube structure is also not affected by temperature, so it operates stably and reduces maintenance costs. In section 2, we show first the newly developed system as a whole and next explain each component of the system in detail. In section 3, we show optical simulation for the design of parabolic mirror and the experimental results which show the proper working verification of two-axis sun-tracking system and the improved performance of our system over conventional OFDS. In section 4, we introduce on-site application of our system, and we conclude our work in section 5.

## 2. System Design

The design of a proposed daylighting system for indoor illumination is presented in this section. Figure 1 shows the diagram of the system. It comprises a collector, a transporter, and a luminaire. The collector is a double parabolics. The concentrator is equipped with a sun tracking system to collect sunlight in the optimum direction. The light transport using a light tube guides the light into deep of a building with high efficiency. Finally, the light will be distributed by luminaire part for uniform and stable illumination.

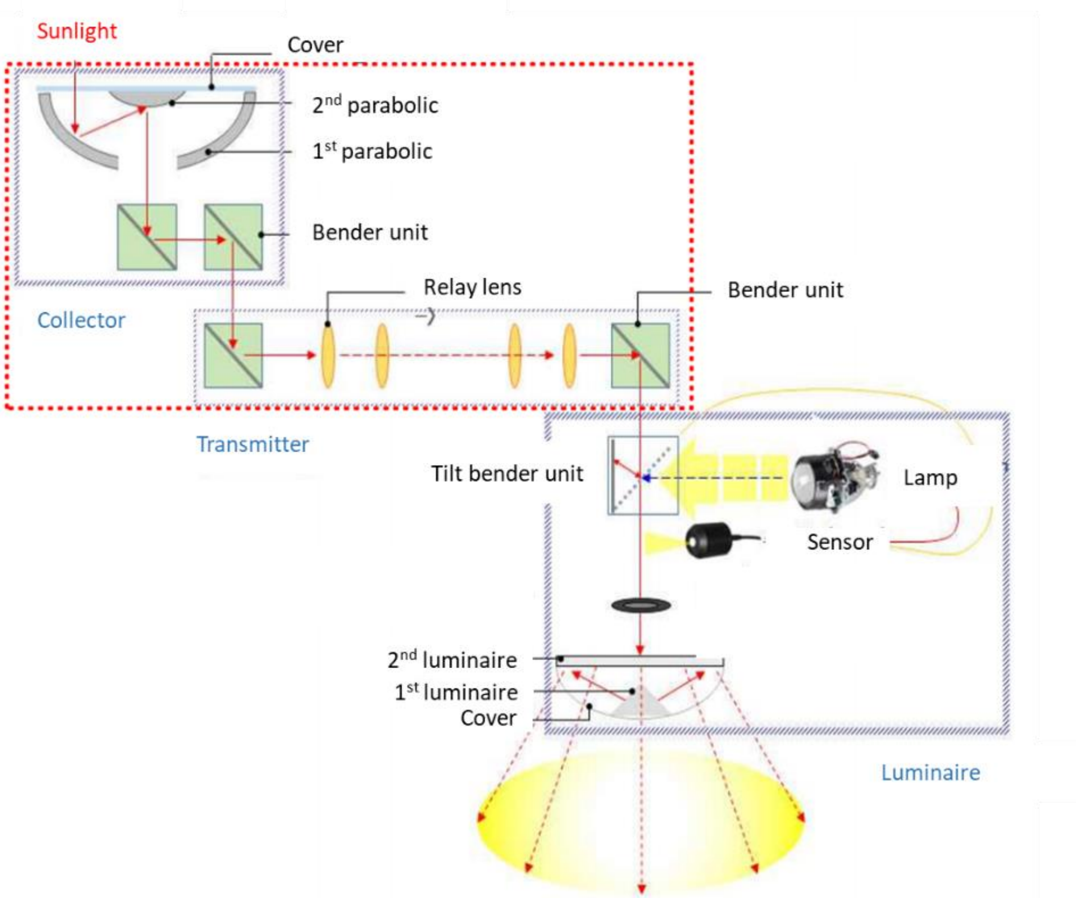


**Figure 1. Schematic diagram of the proposed daylighting system.**

## 2.1 Sunlight Collector

In concentrated solar energy applications, the parabolic reflector is popular. They are used to achieve a high concentration of sunlight. The idea behind the system is to capture sunlight and then focus it to the light pipe. In this study, we used double parabolic to capture sunlight. The light is concentrated through the first primary parabolic reflector, then the light is reflected toward the secondary parabolic reflector to make the light collimated and inserts into light pipe.

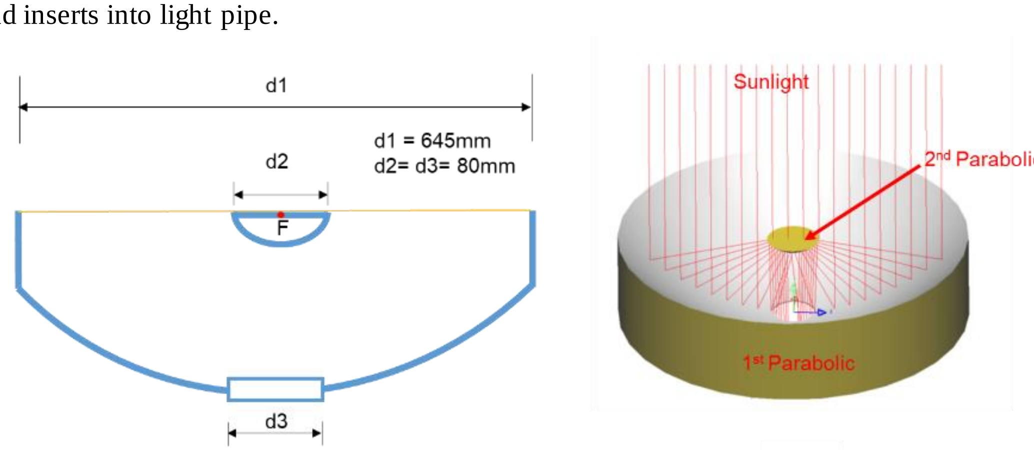


**Figure 2. Schematic diagram of the double parabolic collector**

To achieve collimated light, both reflectors should have the same f-ratio. A parabolic reflector is designed by:

$$y = \frac{x^2}{4F} \tag{1}$$

where y is the value on vertical axis, x is the value on horizontal axis, and f is the focal length.

The first parabolic reflector has a focal length f1 and focal point F. In Figure 2, you can see that focal points of both parabolic are the same. The initial conditions of the parabolic surface have been assumed as shown in Figure 2. From these facts, the equations of parabolic can be calculated [8]. Parameters of the two parabolics are shown in Table 1.

**Table 1. The design parameter for double parabolic collector**

| Double parabolic Specifications | | |
|---|---|---|
| 1st Parabolic | Focal length | 220 mm |
| | Diameter | 645 mm |
| | Material | Aluminum with mirror coating |
| | Reflectance | 99% |
| 2nd Parabolic | Focal length | 32 mm |
| | Dialmeter | 80 mm |
| | Material | Aluminum with mirror coating |
| | Reflectance | 99% |

### 2.2 Bender Unit in Between Collector and Transmitter

Our daylighting structure uses bend unit to redirect the focused beam to the transmission unit. The goal of the unit is to provide a fixed and stable light beam when the position of the collector moves as it tracks the sun position. The structure of bender unit is shown in Figure 3.

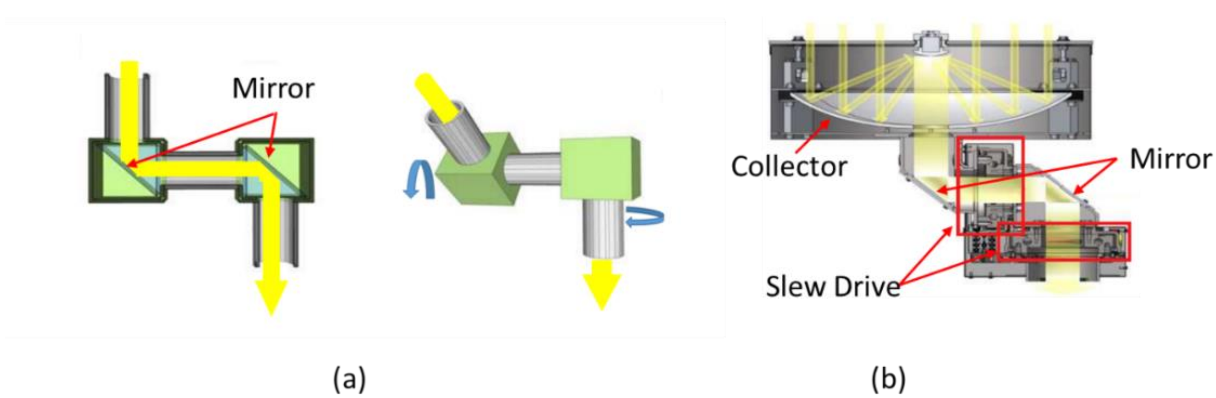


**Figure 3. Schematic diagram of the bend units, (a) principles, (b) mechanical structure.**

The operating principle of this unit is similar to periscope [9]. It is based on the reflection of two mirrors combined with two slew drivers. The mirrors at each end set parallel to each other at 45° degrees. So, the position of the output beam at the exit port of bending unit is fixed during operation.

### 2.3. Light Pipe Daylight Transmitter

Sunlight is concentrated and collimated by using double parabolic collector. Since the direct sunlight reaches to the collector at an incidence angle of less than 0.26°, the maximum incidence angle of concentrated light after double parabolic becomes 0.52°, which means it diffuses during long-distance transmission. Long-distance transmission is impossible without making the light parallel continuously. In order to solve this problem, as shown in Figure 4 (a), an aspherical reflective mirror and relay lenses are used.

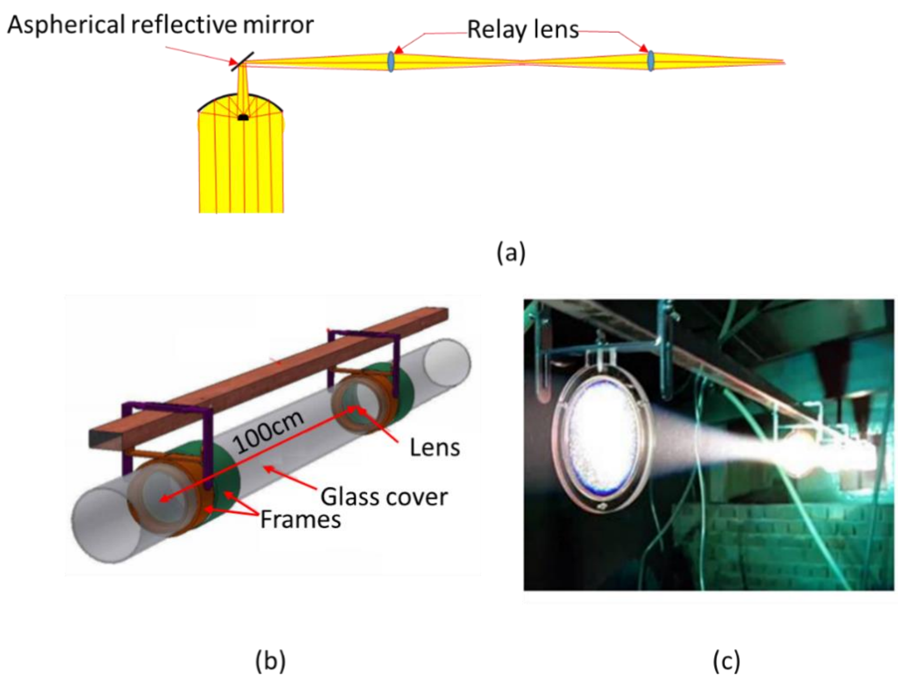


**Figure 4. Implementation of parallel light using aspherical reflective mirror and relay lenses, (a) principles, (b) mechanical structure, (c) installation structure**

We used spherical relay lens with material of BK7. The specifications are as in table 2. The distance between the relay lenses is difficult to determine precisely due to the impact of external installation conditions. In practice we will install the lenses every 1 meter as shown in Figure 4 (b).

**Table 2. The design parameter of relay lens**

| Relay lens Specifications | | |
|---|---|---|
| Surface | S1 | S2 |
| Radius | 520 mm | 520 mm |
| Material | BK7 | BK7 |
| Clear aperture | 94 mm | 94mm |

### 2.4. Distributor

In this study, we developed the hybrid diffuser to mix natural and artificial light together to improve the comfortableness of visual environment. For this purpose, the hybrid light diffuser is installed at the end of the optical transmission pipe as shown in Figure 5.

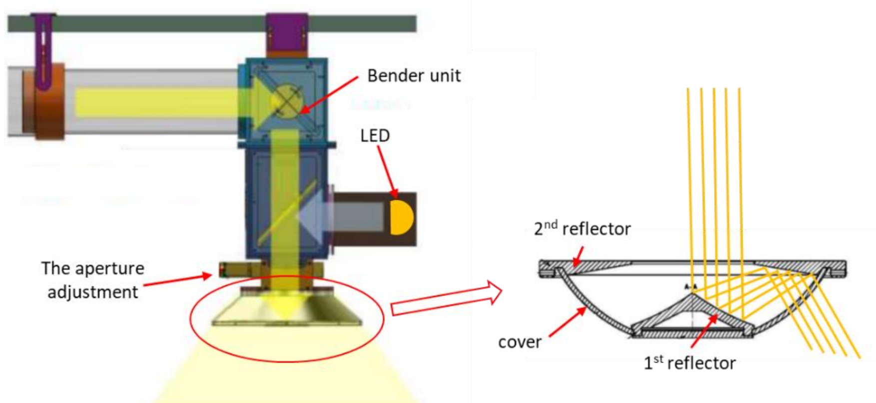


**Figure 5. Schematic diagram of the hybrid diffuser**

We install aperture control unit before the distributor. When the illuminance of the incident sunlight exceeds 110% of the target illuminance, the artificial light source turns off and the controller will adjust the aperture closing range to achieve the target value. If the illuminance of the incident sunlight is not reached the target value, the proper illuminance of light output will be achieved by adjusting the artificial light source and opening the aperture to the maximum. Finally, the light diffuses at the distributor and the glare of light is reduced a lot by two reflectors inside the distributor for indirect lighting.

## 3. Optical Simulation and Experimental Results

### 3.1. Optical Simulation for Parabolic Mirror Design

The commercial optical modeling software LightTools™ was used to design and simulate the geometrical structure of the system. The sunlight source we used in the design was generated by LightTools™, and it has spectrum range of 250–2500 nm. The structure of sunlight collector for simulation is shown in Fig 6.

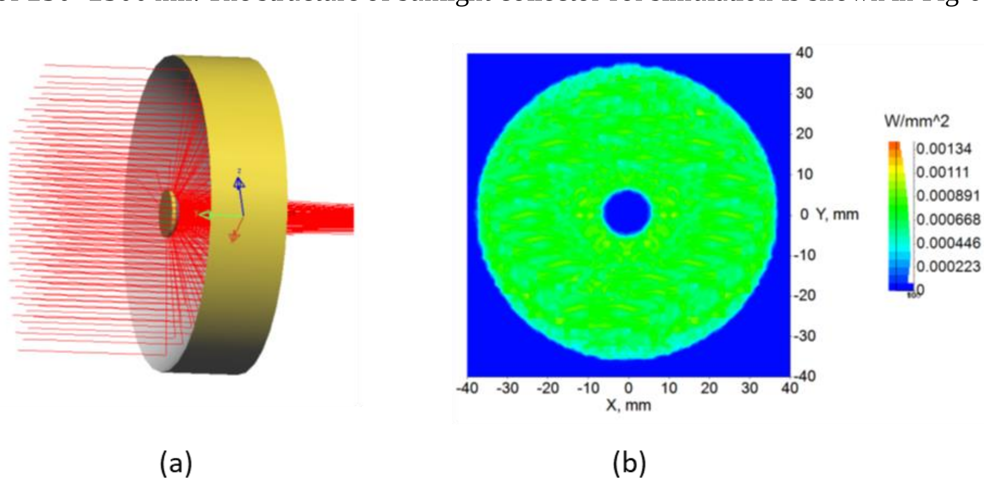


**Figure 6. (a) Schematic of double parabolic collector, (b) illumination on the surface of receiver**

The optical efficiency, which is defined as the ratio of the output luminous flux to the input luminous flux is 92%. The loss is due to many factors such as absorption of the parabolic surface, chromatic aberration with the solar spectrum and non-ideal parallel beam of sunlight. With the receiver of 1 meter away from the parabolic surface, the distribution of the concentrated light with a diameter of 75mm also asserts that the beam generated by the double parabolic is not a perfect parallel beam, therefore, to keep the beam collimated continuously in the light tube, relay lenses are indispensable.

### 3.2. Verification of 2-Axis Sun Tracking System

In order to verify the system's operation, specially, sun-tracking, the system was installed on the terrace as shown in Figure 7. This experiment is confirmed the movement of the output beam. Since our daylight system uses a fixed light pipe, the position of the output beam at the exit port of bending unit must be fixed during operation.

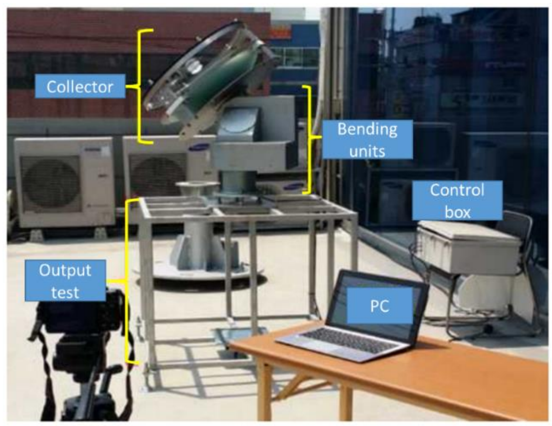


**Figure 7. Experiment to verify the proper operation of the system**

The shape of output beam at the exit port of bending unit was observed from 10:00 to 18:00 at 1-hour interval and the movement of the output beam over time was observed as shown in Figure 8. After 8 hours of experiment, it was confirmed that the output area has moved to the left by 2 mm at maximum. However, this deviation has become reset (0mm) in the next day at the same time of 10am.

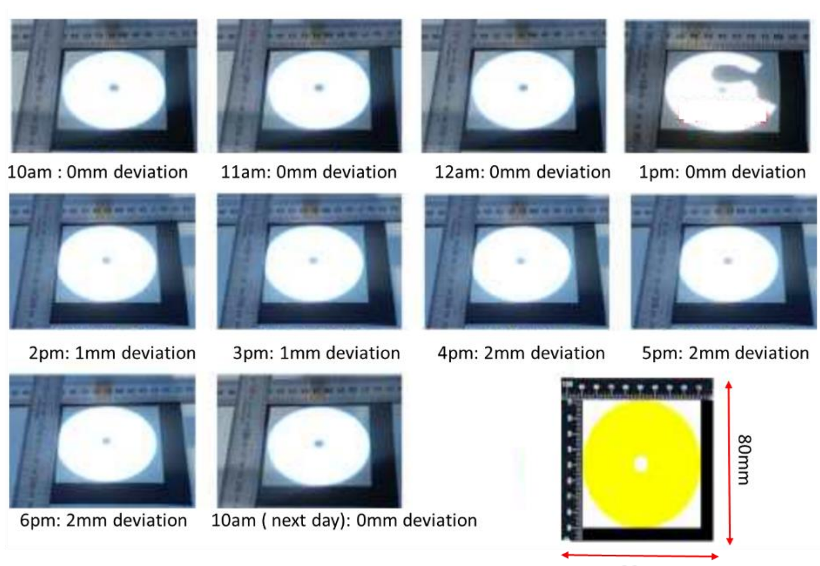


**Figure 8. The shape of output beam at the exit port of bending unit for 8 hours test**

### 3.3. Performance Measurement

The performance of the daylighting system is measured in terms of light transmission distance and indoor illumination of the distributor. To show superior performance characteristics of our system, we compare the proposed system with the commercial fiber daylighting system in reference [10]. The measurements of two systems were taken simultaneously at the same spot as shown in Figure 9. The light transmission distance of our system was 30m and that of the fiber optic daylighting system was 20m.

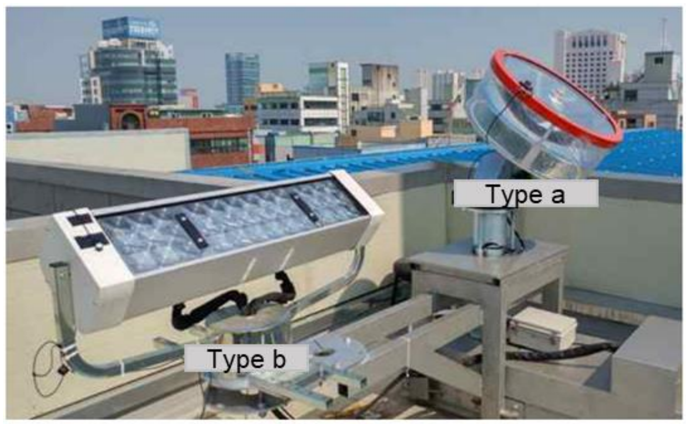


**Figure 9. Performance measurements of our proposed system (type a) and the commercial fiber optic daylighting system (type b)**

The luminous flux was measured using an integrating sphere and a light distribution device. In case of our system, the lighting output efficiency (LOE) is 35.13%, and the total loss rate is 64.87% at 30m transmission. This value is the sum of the lens loss rate 53.2% (28 lenses) and the loss rate of collector and bender units as 11.7%. The LOE of the fiber optic daylighting system is 27.67%, the total loss rate is 72.33%. The LOE is defined by the equation below:

$$LOE = \frac{Flux\ on\ output}{Flux\ of\ the\ receiver} \times 100\% \tag{2}$$

For illuminance measurement, the distributor as a form of diffuser was installed in the test room with the height of 3m from the floor. The light shining area was adjusted to diameter of 3m by the lens. The indoor illumination was measured by a 5-point method as shown in Figure 10.

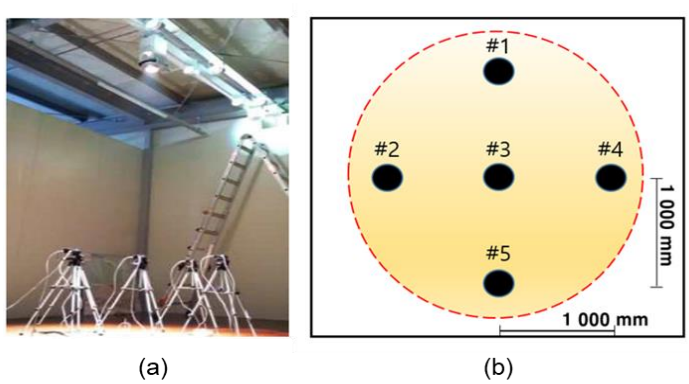


**Figure 10. Indoor illuminance measurement; (a) measurement system, (b) location of the lighting sensor.**

The average illuminance of our system is 3242lx, and the average illuminance of fiber optic daylighting system is 1061lx when external illuminance is 110000lx. Despite the transmission distance of 30m, our system shows about 3.05 times higher illuminance.

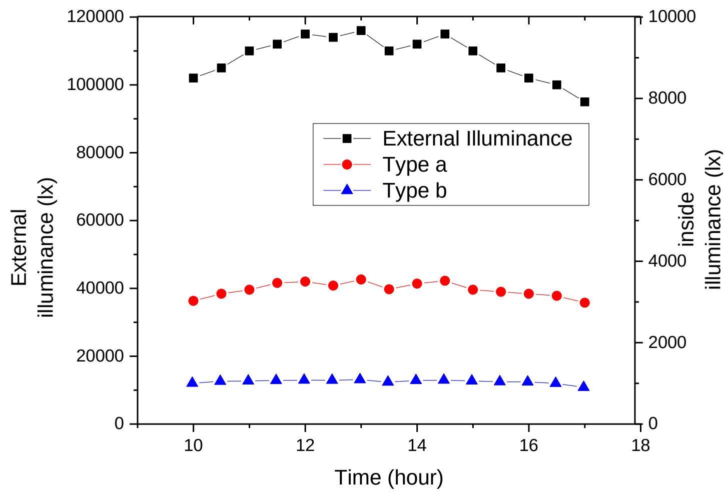


**Figure 11. Illuminance measurement comparison of our propose system and the commercial fiber optic daylighting system.**

## 4. On-site Application of the System

The system we designed was commercialized and installed in Jonggak subway station, Seoul, South Korea. The subway underground place where our natural lighting is provided is called Jonggak station Solar Garden. There are various kinds of plants growing in the garden including lemon trees and many flowers. The luminance of light in the garden is controlled by sensor-based hybrid lighting system which has LED lightings also. The natural light for solar garden is come from 8 sunlight collectors constructed on the ground above subway station in front of Jongno Tower Square as shown in Figure 12.


(a) (b)

**Figure 12. Commercial product of our daylighting system; (a) The system is installed at Jonggak subway station, (b) 8 solar collectors in front of Jongno Tower Square.**

The commercial system is similar to the laboratory system. The only difference is the light transmission distance. For commercial one, this distance is 15-20m. We have also performed experiments to verify the commercial system's performance. The measurement conditions are the same as in section 3.3 with an optical transmission length of 15 m. The lighting output efficiency of 42.3% and the total loss rate of 57.7% were measured for 15m transmission distance.

## 5. Conclusion

In this research, we proposed the daylighting system with modified light pipe for longer transmission distance and higher lighting output efficiency. The proposed system includes light capturing, transmitting, and distributing modules. We achieved better efficiency in terms of illuminance and transmission distance. As a result, comparing with commercially available fiber optic daylighting system, our system can provide 3.05 times higher illuminance for 1.5 times longer light transmission distance. We also successfully installed our commercialized system in the subway station, downtown in Seoul, South Korea.

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