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Design of Solar Lighting System for Energy Saving

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***Abstract*—Recently, it has been found that more consideration has been given to the interaction between buildings, energy, and the environment. Daylighting offers pleasant visual environment and healthy working space and reduces the dependence on artificial lighting, which is the major source of power consumption in buildings. Traditional fiber-based systems were not able to achieve uniform illumination. To this end, we present a study on the use of the optical fiber and solar concentrator for solar lighting system. The solar energy, in the form of light, is collected, guided, and spread through a sun-tracking concentrator, optical fibers, and optics diffusing structure, respectively. A solar lighting system is proposed by using a parabolic reflector. Since it is necessary for fiber-based system to create collimated light for achieving high efficiency, we attained collimated and uniform light at the collecting stage through a collimating device. LightTools, DIALux and SolidWorks are used to design and simulate the daylighting system. The results clearly reveal that the efficiency in terms of uniform illumination is improved. Finally, the proposed solar lighting system will turn out convenient in terms of energy saving and reduction in greenhouse gas emissions.**

Keywords—solar energy; daylighting; uniform illumination; optical fiber; ray tracing

I. INTRODUCTION

People living in urban areas spend most of their daylight hours under artificial light, and it has been researched that individuals are susceptible to detrimental effects in the absence of daylight [1]. Conventional candescent and fluorescent lamps have been indicated in aggravating depression, aggression, eye strain, reduced muscle strength, obesity, and diabetes [1]. Consequently, daylight should be diffused in the interior for healthy indoor environment.

Daylighting has a significant role in the field of renewable energy in terms of reducing the use of electricity, which has been significantly increasing in many countries [2]. A reduction in energy consumption and the production of energy through renewable energy sources can lead to a lower production of greenhouse gas emissions, which is becoming an increasingly serious global issue [2]. Buildings, especially office buildings, are the main source of power consumption and greenhouse gas emission, and electricity demand is growing by 0.7% per year in buildings in the U.S.A. [2]. It has been estimated that energy consumption in residential and commercial buildings is nearly 40.40% of the total energy consumed in the U.S.A. [3]. Therefore, more attention has been paid to energy consumption in buildings, where lighting is the major source of energy utilization. Energy consumption due to electric lighting in buildings is approximately 40–50% of the total energy cost [4]. One of the reasons is that the growth of lighting demand is increasing due to rising average illuminance levels in buildings, especially in newly constructed buildings. Therefore, sustainable buildings have been developed. One of the principles of sustainable buildings is to illuminate the building by daylight instead of artificial light at all times of the day to reduce the overall energy consumption of the building. Efficient daylight buildings are estimated to reduce electric lighting energy consumption by 50–80% [5]. Thus, an appropriate daylighting strategy will lead us to a solution to the energy problem.

In sustainable development, the interior of buildings is illuminated by daylight through the windows and the daylighting systems. During the architectural design process, an important consideration is given to daylight accessing the interior of buildings through the windows and the openings. Since buildings usually have windows, 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. According to European Standard, the requirement for the office buildings is to achieve an average illuminance of 500 lx [6]. However, it is difficult to achieve 500 lx at all times of the day through only windows and openings. Therefore, a daylighting system is needed to illuminate all the dark areas of the building during the day with electric lighting controls to reduce power consumption.

Several concepts regarding daylighting systems have been demonstrated with light pipes [7-11] and optical fibers [12-26], and most of the designs have a large number of tracking reflectors and lenses, and, thus, require a large area in which to be installed.

We analyzed losses and improved two fiber-optic daylighting systems using a parabolic reflector and Fresnel lens through simulation and real experiments [12]. During the development, the efficiency of the system was improved via uniform and collimated illumination on the fiber bundle and by reducing the heat problem, which had critical importance for the plastic optical fiber (POF) to make the system cost effective.

The main purpose of this study is to achieve uniform light into the optical fibers and to deliver it to building interiors. Consequently, we propose a novel approach for the parabolic reflector. Sunlight is concentrated and focused toward the collimating lens, and then collimated light is transmitted into optical fibers. To make the system cost effective, POFs are used for most of the transmission.

There has been a trend toward reducing the power consumption of electric lighting via new technologies. The possible ways to do this include the use of lighting control systems, the use of light sources with high luminous efficacy, and the utilization of daylight. High-performance light-emitting diodes (LEDs), compact fluorescent lamps, and incandescent lamps are used to replace low-efficacy light sources. To maintain the required illumination level at all times, the system must be able to compensate for when daylight is not available; thus, LED light sources are used due to their high efficacy. Furthermore, a hybrid system gives better illumination quality. This research also improves the efficiency of the hybrid, optical fiber-based daylighting system.

In this research, we present a simulation study of the proposed approach. LightTools®, which is a well-known, optical-simulation tool [12,13], is 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) are considered in the simulation to analyze the performance of the system efficiently. SolidWorks™ is used to design some mechanical parts. DIALux™, which is widely used for indoor and outdoor lighting simulation [27], is used to show the room's interior view under lighting simulation.

The remainder of the paper is organized in the following manner. Section II describes background. The proposed daylighting system is discussed in Section III. In Section IV, light-transmission media and the light distribution in the interior are detailed. The complete study, involving the simulation, the evaluation of the results, and comparisons of the differing architectures are presented in Section V. Finally, brief concluding remarks and future work are included in Section VI.

II. BACKGROUND

To date, most studies have been dedicated to active daylighting systems, which include sun tracking module. Because these systems have high efficiency, they are preferred to install. Most of the daylighting systems have issue of non-uniformity. In this section, we will discuss non-uniformity issue in previous approaches [24-26]. We used our own measurements for illustrating non-uniformity.

The idea of capturing high-intensity sunlight has been demonstrated in which a parabolic reflector concentrated sunlight into a single optical fiber through a flat mirror [24], as shown in Fig. 1(a). For light transmission, fused-silica optical fibers were utilized. The optical fiber had a diameter of 1 mm, and the parabolic dish had a diameter of 0.2 m. After reflection of the light at the parabolic surface, most of the light was lost through it hitting the outer surface of the optical fiber. As a result, most of the light was not able to reach the flat reflector. They used small parabolic dishes to collect sunlight. However, the large number of parabolic dishes occupied a large area. Each parabolic dish needed a separate sun-tracking module, which increased the cost of the system. The system was used for solar thermal applications to produce energy rather than daylighting. For daylighting, a system should contain a minimum number of concentrators. Therefore, this approach is not suitable for installing the concentrators on the roofs of buildings. If a fiber bundle is used instead of a single optical fiber with this approach, uniform illumination will not be obtained, even with a very high concentration of light.

In [25], they used parabolic and hyperbola reflectors for light capturing. The light was concentrated through a parabolic reflector and then light is reflected toward the hyperbola reflector. The light is inserted into optical fibers to transmit it into the interior. In this approach, we found two problems: the heat problem and non-uniformity. The central optical fibers in the bundle were over shadowed due to the blockage of direct sunlight from the hyperbola reflector, and some optical fibers had high intensity of light, as shown in Fig. 1(b). Thus, the bundle of optical fiber was illuminated non-uniformly.

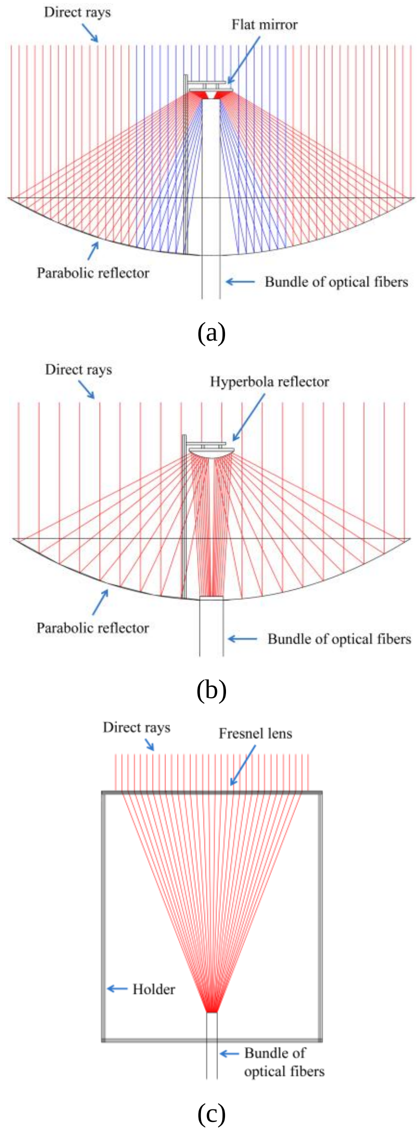

Figure 1. Physical layout of the system for the (a) parabolic and flat reflectors (b) parabolic and hyperbola reflectors (c) Fresnel lens.

In the Himawari solar lighting system, Fresnel lens was used to collect sunlight [26]. The light was focused through a Fresnel lens, and only visible light was inserted into optical fibers, as shown in Fig. 1(c). It had two series of models with a different number of lenses and optical fibers in the bundle. All models contained quartz-glass optical fibers (QOFs), which exhibited low losses during light transmission. However, the system was costly due to the price of QOFs. The system combined six optical fibers in each bundle for light distribution, and the illumination angle from the fiber bundle was 58 degrees. The luminous flux per cable was 1920 lm. Overall, the light capturing and distribution method was not well defined in this design in terms of it achieving uniform illumination.

III. PROPOSED DAYLIGHTING SYSTEM

A parabolic reflector is used to achieve a high concentration of sunlight. In Fig. 2, sunlight collecting unit using the parabolic reflector and collimating lens is shown. Direct sunlight hits the surface of the reflector and reflected toward a collimating lens to create uniform light. After being collimated, the light is entered into optical fibers. Uniform illumination was accomplished through the collimating lens by

$$D_p = D_r \tag{1}$$

where D_p is the diameter of the concave region of the plano-concave lens and D_r is the diameter of the receiver (bundle of optical fibers). The focal length of the collimating lens was calculated by [28]

TABLE I. MEASUREMENTS OF DIFFERENT PARAMETERS

Title	Value (mm)
Diameter of parabolic reflector	320
Focal length of parabolic reflector	276
Depth of parabolic reflector	23.2
Diameter of plano-concave lens	18
Focal length of plano-concave lens	18.7
Diameter of the bundle of optical fibers	14.4
Distance between reflector and lens	261

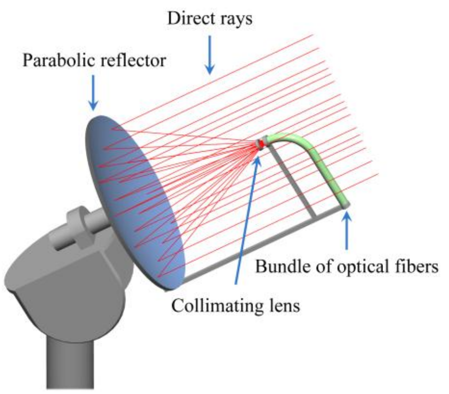

Figure 2. Scheme of the proposed daylighting system.

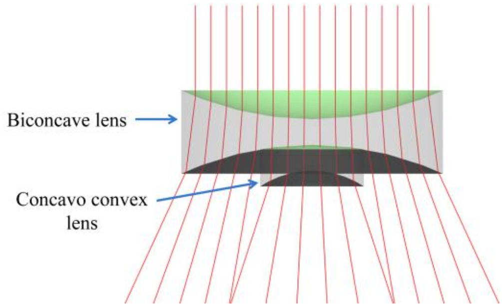

Figure 3. Behaviour of the incident light on the diffuser lens.

$$NA = n \cdot \sin\theta_{1/2} = \frac{D}{2f} \tag{2}$$

where *NA* is the numerical aperture of the concentrator and *D* is the diameter of the collimating lens. Measurements of reflectors, lenses, and other parameters are shown in Table 1.

IV. SUNLIGHT TRANSMISION AND DISTRIBUTION

We used silica optical fibers to reduce heat problem, and POFs were used for most of the transmission part due to their low cost, flexibility, strength, and acceptability for complex wiring in buildings. POFs have a core diameter of 1.98 mm and a cladding diameter of 2 mm.

Recently, numerous approaches have been presented to achieve uniform illumination from light sources [29]. In solid-state lighting, this issue has gained critical importance. Similarly, uniform illumination is mandatory in daylighting. To spread the light from the optical fibers, which had a high beam of light, they were divided into different bundles, and optical fibers in each bundle were organized into a circular shape. Each fiber bundle covered a surface area of 78.54 mm^2. A diverging lens was the best choice for the light distribution. The focal length of the thin lens can be determined by the lens maker's formula, which can be written as [30]

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{3}$$

where r_1 and r_2 are the two radii and n is the refractive index of the material. The lenses had a refractive index of 1.459. In [12], we used a biconcave lens at the end side of the fiber bundle to diverge the light. In present study, we used a combination of a biconcave lens and a concavo convex lens, as illustrated in Fig. 3.

TABLE II. MEASUREMENTS OF LENSES

Title	Value (mm)
Radius of biconcave lens	12
Focal length of biconcave lens	13.2
Focal length of concavo convex lens	11.3
Radius-1 of concavo convex lens	12
Radius-2 of concavo convex lens	3.6

TABLE III. AVERAGE ILLUMINANCE AT DIFFERENT TIMES OF THE DAY AND THE CALCULATED FLUX FOR THE CONCENTRATOR.

Time	Outdoor illuminance (lx)	Input flux (lm)	Indoor illuminance (lx)
12 PM	110000	11255	756
1 PM	105000	10745	722
2 PM	100000	10240	688
3 PM	80000	8186	550
4 PM	60000	6140	413
5 PM	40000	4093	275
6 PM	20000	2047	138

V. RESULTS FROM SIMULATION

We simulated the proposed approach using optical software (LightTools®) to prove that the daylighting system can offer required illumination. For daylight, lumens was calculated to simulate the entire optical design for indoor by [31]

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

where E' is the measured illuminance, dF is the input luminous flux in lumens, and dS is the area of the concentrator. We calculated the simulated input flux from the measured illuminance by using Eq. (4). The measured illuminance at different times of the day at outdoor and the calculated flux are mentioned in Table III. To check illuminance uniformity on the fibers' ends, 500 K rays were used. In Fig. 4, we show simulation results that were achieved from different designs. The light on each optical fiber is not uniform, as shown in Figs. 4(a) and 4(b). In Fig, 4(c), the illuminance value is less than our proposed design. As evident from Fig. 4(d), uniform illumination was achieved in the bundle of optical fibers through the proposed approaches, and each optical fiber had similar illuminance. We have reduced shadow on the fiber bundle, as compared to the previous approach for the parabolic reflector [12].

We mounted two systems to illuminate an area of 24 m^2. To distribute daylight in the interior, fibers were arranged into six bundles, and then placed at different positions to illuminate the interior. Each fiber bundle had fifty five optical fibers. Our main goal was to illuminate a large area with an average illuminance of more than 500 lx. To use small lenses for the distribution of light, optical fibers in each bundle were organized to form a circular shape. The candle power distribution curve of fiber bundle is shown in Fig. 5. Illuminance distribution in the interior and on the working plane is shown in Figs. 6 and 7, respectively. The illuminance uniformity of a given space (plane) is calculated by

$$Unifomity = \frac{E_{min}}{E_{avg}} \tag{5}$$

where E_{min} is the minimum level (value) of illuminance and E_{avg} is the average level (value) of illuminance. We achieved illuminance uniformity of 0.3 and 0.7 on the work plane and floor, respectively.

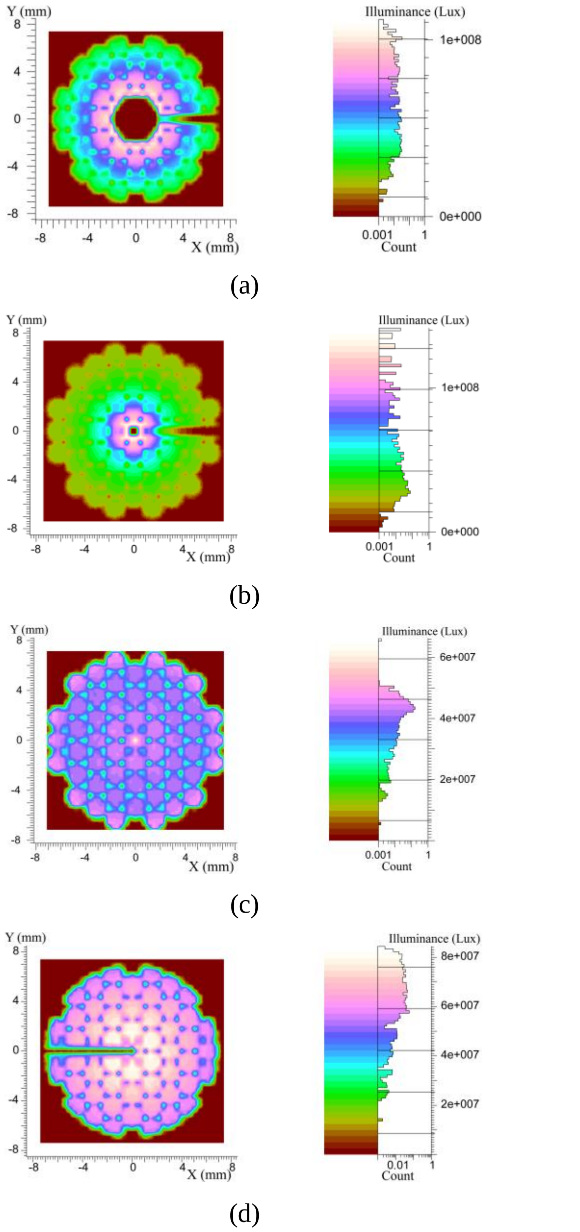

Figure 4. Uniform illumination on the surface of optical fibers' ends for the (a) parabolic and flat reflectors (b) parabolic and hyperbola reflectors (c) Fresnel lens, and (d) proposed approach.

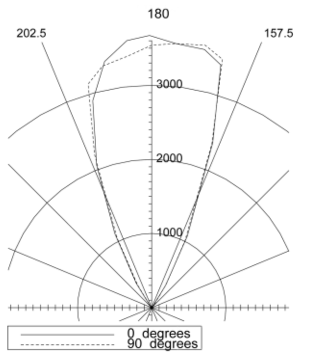

Figure 5. The candle-power distribution curve of the fiber bundle.

Figure 6. Illuminance distribution in the interior.

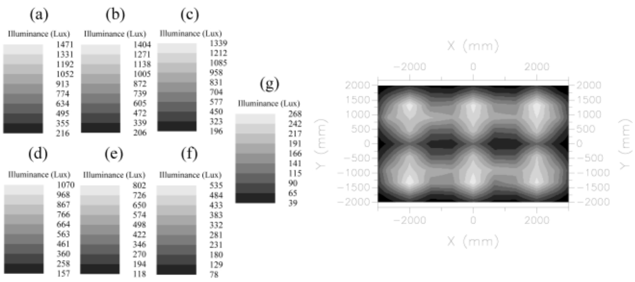

Figure 7. Illuminance distribution on the working plane by daylight.

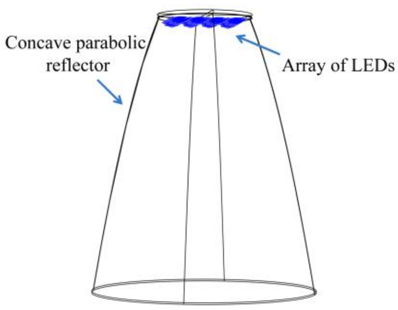

Figure 8. Scheme of LED light source.

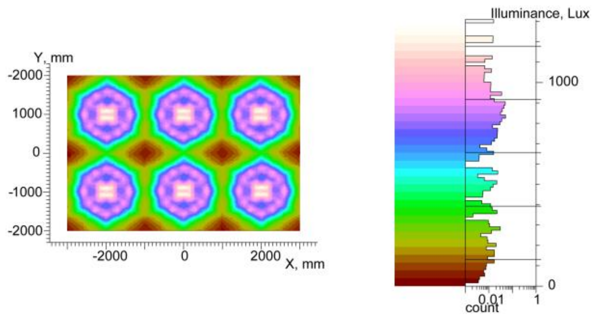

Figure 9. Illuminance distribution on the working plane by LED light.

To attain the required illuminance of 500 lx, which is the minimum requirement [32], in the office when sunlight fell from the required range, we made use of LED sources. The LEDs were placed by feedback from a light sensor. When the daylight was strong, the LEDs were turned off. When illuminance of the daylight was insufficient, LEDs were turned on automatically to meet the deficiency. OSRAM™ LW W5AM LEDs were used, which have the maximum optical efficiency of 130 lm/W [33]. As shown in Fig. 8, 24 LEDs were arranged to make a single source of light, which illuminated an area of 4 m^2. Six LED light sources were arranged to illuminate an area of 24 m^2. We used 100 K rays from each LED to carry out the simulation. An average illuminance of 550 lx was achieved from the LEDs, as shown in Fig. 9.

Since a control unit was installed to maintain an average illuminance of 500 lx in the interior, a constant illuminance was provided at all times [11]. For example, when the average illuminance was 300 lx around 5pm, the remaining illuminance of 200 lx was provided by LEDs through the control unit.

VI. Conclusions

The proposed daylighting system includes light capturing, transmitting, and distributing parts. To capture sunlight, we designed collecting module using parabolic reflector, and a collimating lens was used for uniform illumination. We achieved better efficiency in terms of illuminance uniformity and light flux than that of previous approaches. For light transmission, we used plastic optical fibers to make the system cost-effective. To distribute sunlight in the interior, an optical lens structure was used for uniform illumination. As a result, we achieved uniform illumination. Furthermore, we introduced a hybrid system by using LEDs.

To investigate the system, we considered an office building. The system was developed and applied to the office room. Results have shown that the interior of the room was illuminated uniformly with an average illuminance of more than 500 lx. In the future, we will improve light uniformity in the interior of the building by designing an efficient diffuser.

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