Development of optical fiber-based daylighting system with collimated illumination

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Abstract

Uniform illumination for optical fiber-based daylighting system is acquired at capturing and distributing stages, and efficiency of the system is increased by collimated light. Two approaches are proposed for parabolic mirror and Fresnel lens.

I. INTRODUCTION

Solar energy is one of the main sources for electricity production, and it can be used for thermal applications and daylighting. The main source of power consumption and greenhouse gas emission in the whole world are buildings. In the buildings, power consumption due to electric lighting is becoming a critical problem, and 40 to 50 percent of the total energy is consumed for lighting in buildings [1]. The research on office buildings indicates the failure to provide comfortable indoor environments. One of the reasons is the use of artificial light instead of sunlight. Different architectural designs for buildings have been introduced to illuminate the building by introducing windows and other open places in the building, but daylight levels decrease very rapidly from windows. Therefore, daylighting system is essential to illuminate all the dark areas of the building at the daytime. In past studies, different daylighting systems have been demonstrated using optical fibers [2]. Furthermore, the distribution of uniform light is becoming a critical issue in the solid-state lighting. Similarly, this issue is more serious in the daylighting system. Our current research and development shows an improvement to deliver high intensity light at the interior.

II. UNIFORM AND COLLIMATED ILLUMINATION

We propose two efficient approaches for parabolic mirror and Fresnel lens to achieve collimated light. The bundle of optical fibers is illuminated uniformly using both approaches. LightTools™ is used to implement the system as shown in Fig. 1. Concave and convex parabolic reflectors are appropriate to produce collimated light as shown in Fig. 2(a). Correct placement and measurements of reflectors to make collimated light can be achieved by

$$F = F' \quad (1)$$

where F is focal point of the concave reflector and F' is the focal point of the convex reflector. Uniform light on the fiber ends is achieved by

$$D_r = D_c \quad (2)$$

where D_r is the diameter of the receiver (optical fiber) and D_c is the diameter of the convex reflector. In case of lenses, a combination of Fresnel lens and plano-concave lens gives collimated light as illustrated in Fig. 2(b). Uniform illumination is accomplished through Fresnel lens by

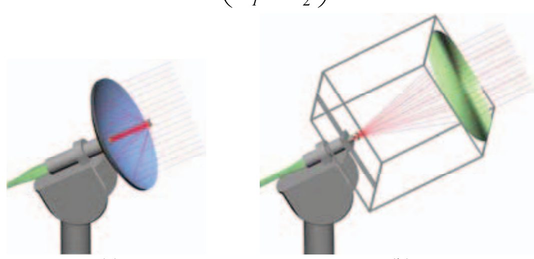
$$D_p = D_r \quad (3)$$

where D_p is the diameter of the concave region of the plano-concave lens. The focal length of the collimating lens can be calculated by [3]

$$NA = n \cdot \sin \theta_{1/2} = \frac{D}{2f} \quad (4)$$

where NA is the numerical aperture of the concentrator and D is the diameter of the collimating lens. Bundle of fifty four and fifty five fibers for parabolic mirror and Fresnel lens are very appropriate to reduce the heat problem, respectively. If we increase the size of the concentrator, after sometime optical fibers start to melt. Oppositely, if we decrease the size of the concentrator, the light intensity becomes less, which affects the efficiency of the system. Therefore, better efficiency and elimination of the heat problem can be achieved by the presented measurements. Another problem is solved by introducing silica optical fiber (SOF) before plastic optical fiber (POF). If the system is moved to another place, which has high intensity of light above the defined limit, some heat will be absorbed by SOFs. Index matching jell is also applied to minimize the losses, and the loss due to the difference in diameter is less because light is entering from a small area to large area. The loss at the input end of fiber is sometime called Fresnel loss and can be calculated by [4]

$$R_f = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 E \quad (5)$$



(a) (b)

Fig. 1. The schematic design of the system with ray tracing for (a) parabolic mirror (b) Fresnel lens.

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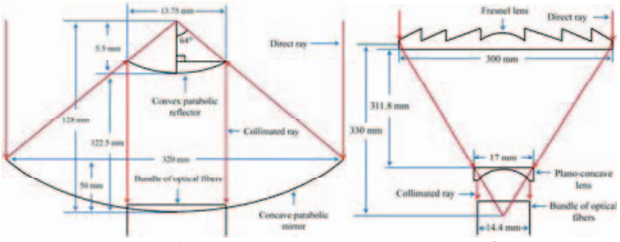


(a) (b)

Fig. 2. The schematic structure to generate uniform and collimated illumination through (a) reflectors and (b) lenses.

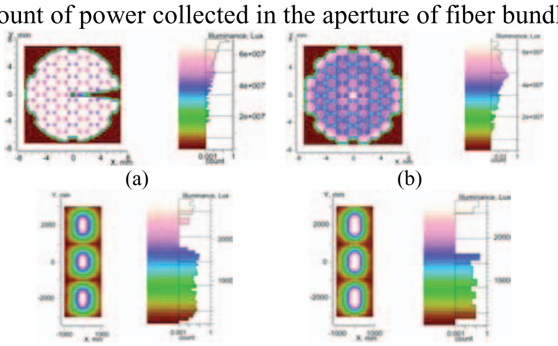
where n_1 and n_2 are the refractive indices of the two mediums, and E is illuminance. In our case, light entered from air to SOF, giving n_1 = 1.457 and n_2 = 1.00. For daylight, lumens can be calculated to simulate the whole model for indoor, which is given by [4]

$$E' = \frac{dF}{dS} \qquad (6)$$

where E' is the measured illuminance, dF is the input luminous flux in lumens, and dS is the area of the concentrator. Calculated flux for different illuminance values are mentioned in Table 1.

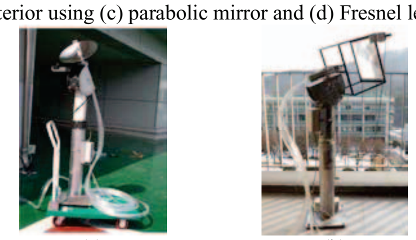
III. Simulation and Experimental Results

The system was illuminated by inserting illuminance of 100 Klx, and illuminance was measured on the surface of optical fibers. As evident from Fig. 3(a) and Fig. 3(b), uniform illumination is achieved on the surface of fibers bundle. In order to distribute daylight at the destination, fibers are arranged into three bundles, which are placed at different positions to cover a surface area of 12 m^2. Optical fibers in each bundle are organized in a circular shape to use small biconcave lenses for light distribution. Illuminance was measured at 2 m distance below the roof of the office as shown in Fig. 3(c) and Fig. 3(d). Hardware designs for both approaches are developed to verify the proposed system as depicted in Fig. 4. The amount of power collected in the aperture of fiber bundle



(a) (b) (c) (d)

Fig. 3. Uniform illumination on the fiber ends through (a) parabolic mirror and (b) Fresnel lens. Daylight illuminance distribution at the interior using (c) parabolic mirror and (d) Fresnel lens.

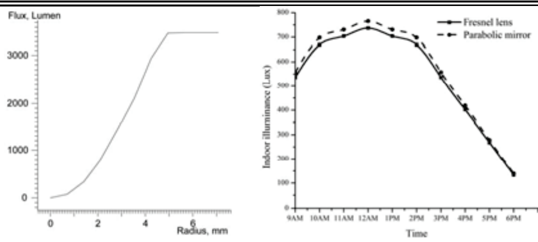


(a) (b)

Fig. 4. Manufactured daylighting system with sun tracking for (a) parabolic mirror and (b) Fresnel lens.

TABLE I
AVERAGE ILLUMINANCE AT DIFFERENT DAYTIMES AND CALCULATED FLUX FOR EACH CONCENTRATOR

Time	illuminance (lx)	Flux (lm) for Parabolic mirror	Flux (lm) for Fresnel lens
9 a.m.	80000	8186	8500
10 a.m.	100000	10240	10627
11 a.m.	105000	10745	11159
12 p.m.	110000	11255	11691
1 p.m.	105000	10745	11159
2 p.m.	100000	10240	10627
3 p.m.	80000	8186	8500
4 p.m.	60000	6140	6372
5 p.m.	40000	4093	4248
6 p.m.	20000	2047	2125



(a) (b)

Fig. 5. (a) Encircled energy is represented, which shows the amount of power collected in the aperture of fiber bundle at the interior for parabolic mirror (b) average illuminance at the interior.

can be expressed by encircled energy graph as shown in Fig 5 (a). We have accomplished average illuminance of more than 500 lx as shown in Fig 5(b), which is the minimum requirement for office building [5]. If the illuminance decreases from 500 lx, artificial light from LEDs will be delivered to meet the requirement.

IV. Conclusions

In this paper, two approaches have been presented to eliminate the heat problem and to increase the efficiency of the optical fiber-based daylighting system. Uniform illumination has been achieved for parabolic mirror and Fresnel lens to deliver uniform daylight at different regions of the building (e.g., light distribution at each floor of the building). Efficiency of the system has been increased by collimated illumination and by minimizing the shadow due to convex reflector and mechanical parts. As a result, high intensity of light is attained, which makes the system efficient. The proposed system guarantees to save electric lighting power consumption by delivering an average illuminance of more than 500 lx. Uniformity in the daylight distribution at the interior can be improved by introducing a combination of lenses at the end side of the fiber bundle.

References

[1] A. Ossa, D. A. Gottfried, T. Walsh, and L. N. Simon, “Sustainable Building Technical Manual: Green Building, Design, Construction and Operations, US: Public Technology Inc, 1996.
[2] C. Maxey, “Hybrid solar lighting: fiber optics bring sunlight inside,” Photonics spectra, Issue. 6, 2008.
[3] D. Malacara, Optical Shop Testing 2ndEdition, 1992.
[4] V. N. Mahajan, Optical Imaging And Aberrations - Part 1 Ray Geometrical Optics.
[5] EN 12464-1 Light and Lighting – Lighting of work places – Part 1: Indoor work places, European standard, 2002.