Optical fiber-based daylighting system for multi-floor office buildings

Irfan Ullah and Seoyong Shin
Department of Information and Communication Engineering, Myongji University, Yongin, South Korea

Abstract

Traditional fiber-based daylighting systems were implemented only for small scale. In order to distribute sunlight into the entire building, a large number of optical fibers are needed. We propose a daylighting system that helps to illuminate multi-floor office buildings. Sunlight is captured through parabolic trough, and linear array of optical fibers is illuminated uniformly. Lenses are used to distribute uniform light at the interior. The efficiency of the system is increased by collimated light, which helps to insert maximum light into optical fibers. We have demonstrated the optical design that can significantly reduce power consumption in the multi-floor office buildings, and can improve indoor environments.

I. INTRODUCTION

There has been more demand of energy due to the increase of energy consumption in the buildings. Power consumption due to electric lighting in the buildings is becoming a critical problem, and it is approximately 35.8% in the buildings of Korea [1]. Daylighting has a significant role in renewable energy to reduce power consumption for sustainable development. In order to minimize electrical energy consumption and to improve indoor environments, our main target is to illuminate multi-floor buildings uniformly by sunlight. Days of most office workers are spent in the indoor under artificial light. As a result, 78 million have calcium deficiency due to poor vitamin D [2]. Research clearly recommends that daylight delivers healthy life style and saves electric lighting energy consumption. Therefore, daylighting systems are highly acceptable for buildings, especially for office buildings.

Great efforts have been dedicated to the development of the daylighting systems and to deliver daylight at the indoor from windows and opening places [3]. But since daylight levels decrease very rapidly from window, therefore, daylighting system is compulsory to illuminate all the dark areas of the building at daytime. A variety of possible daylighting approaches have been demonstrated using optical fibers [4]. Previously, it was a problem to make a large-scale system to illuminate a large area of the building. Most of the designs were developed using a large number of tracking reflectors and lenses, and more area was required to install such kind of systems. Our proposed system is expandable with only one tracking module. It can be expended by increasing the rectangular aperture height and width. If the rectangular aperture height is increased, the number of fiber arrays will be increased. In the same way, more fibers will be added by increasing the rectangular aperture width. Therefore, the required design can be easily crated by knowing the required illumination to illuminate different floors of the building.

II. CONCENTRATOR FOR LINEAR ARRAY OF FIBERS

We propose an efficient large-scale system which contains parabolic trough to collect sunlight. This type of concentrating collector can be tracked through single-axis turning or two-axis turning. Parabolic trough captures sunlight, and concave parabolic mirror directs the light onto fiber ends. LightTools™ is used to implement the proposed daylighting system as shown in Fig. 1. The reflective surface area of the parabolic trough can be calculated by [5]

$$A_s = L \cdot S \tag{1}$$

$$S = \left[\frac{d}{2}\sqrt{\left(\frac{4h}{d}\right)^2 + 1}\right] + 2f\ln\left[\frac{4h}{d} + \sqrt{\left(\frac{4h}{d}\right)^2 + 1}\right] \tag{2}$$

where S is the arc length, h is the depth, d is the diameter, f is the focal length, and L is the length of the trough. Trough has rectangular aperture width of 1.7 m to illuminate single floor of area 200 m^2. Number of floors to illuminate can be increased by changing the rectangular aperture width of the trough. Optical fibers are mounted to deliver sunlight at each floor with small losses. In order to solve cost, heat, and efficiency issues, optical fibers are illuminated uniformly. Collimated light is achieved by

$$D_a = D_r \tag{3}$$

Where D_a is the diameter of the absorber and D_r is the diameter of the concave parabolic mirror, where rays hit the surface. Fibers are arranged to make a linear array at the center of trough as described in Fig. 2. In order to solve the issue of high concentration ratio, compound parabolic concentrator (CPC) is introduced before fibers as shown in Fig. 3. The loss at the input end of the fiber is sometime called Fresnel loss and can be calculated by [6]

$$R_f = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 E \tag{4}$$

where n_1 and n_2 are the refractive indices of the two mediums, and E is illuminance. In our case, the light passed from air to PMMA, giving n_1 = 1.495 and n_2 = 1.00. For daylight, lumens can be calculated to simulate the whole model for indoor, which is given by [6]

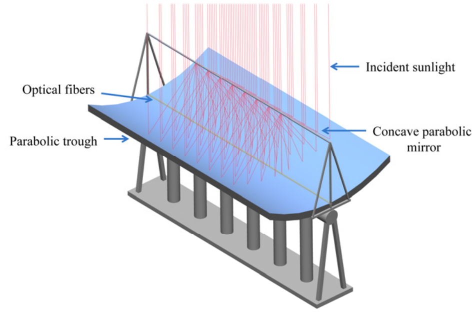


Fig. 1. The prototype concentrator depicting the light path entering optical fibers.

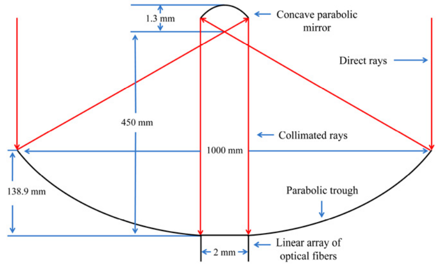


Fig. 2. Collimated light to illuminate linear array of fibers when sunlight is highly concentrated.

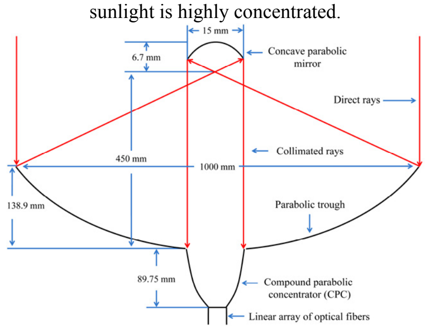


Fig. 3. Illuminating linear array of optical fibers by introducing CPC before fibers.

$$E = \frac{dF}{dS} \tag{5}$$

where E is the measured illuminance, dF is the input luminous flux in lumens, and dS is the area of the concentrator.

III. Experiments and Results

The system was illuminated by inserting illuminance of 100 Klx. Illuminance was measured on the surface of optical fibers. Uniform illumination is achieved due to collimated light as shown in Fig. 4. In order to distribute daylight at the indoor, optical fibers are arranged into bundles, and each bundle has nineteen fibers. In order to spread the light at the destination, biconcave lenses are introduced at the end side. Illuminance is measured at two meter distance below the roof. One bundle illuminates an area of 4 m^2 as shown in Fig. 5(a). Thus, fifty bundles will illuminate an area of 200 m^2 with an average illuminance of 838 lx as mentioned in Fig. 5(b). Illuminance varies all the daytime as mentioned in Fig. 6(a). Therefore, indoor illuminance was measured by inserting different illuminance values as illustrated in Fig. 6(b). In order to maintain average illuminance of 500 lx, which is the minimum requirement for office [7], LEDs are mounted beside each fiber bundle.

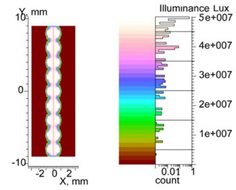
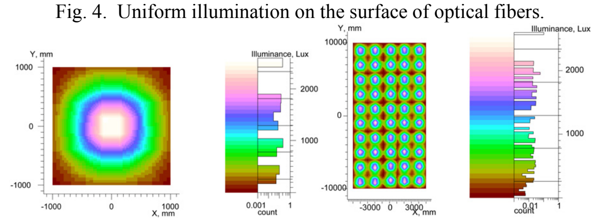
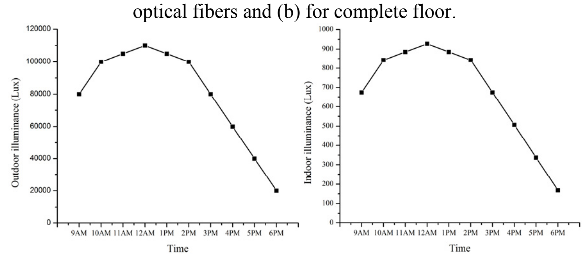


Fig. 4. Uniform illumination on the surface of optical fibers.



(a) (b)

Fig. 5. Distribution of daylight at the interior (a) from single bundle of optical fibers and (b) for complete floor.



(a) (b)

Fig. 6. Different average illuminance values for (a) outdoor (b) indoor.

IV. Conclusions

We have demonstrated an optical fiber-based daylighting system for multi-floor office buildings to illuminate each floor uniformly with high illuminance of more than 500 lx. The proposed system has been highly accepted due to simplicity in the design, easily manageable, applicability of rapid manufacturing, and widely expendable to make a large-scale system. Eventually, efficiency of the system is improved by inserting maximum light into optical fibers. In addition, CPC is introduced before fibers, which helps to solve the issue of perfect alignment and high concentration ratio for the real implementation. Uniformity at the interior can be improved by introducing a combination of lenses at the end side of the fiber bundle.

References

[1] I. Yong and E. Nam, “Economic analysis of the daylight-linked lighting control system in office buildings,” Solar Energy, vol. 84, pp. 1513–1525, 2010.

[2] Dr. A. Dunne, “Some Effects of the Quality of Light on Health,” J Orthomol Med, 4(4), pp. 229-232, 1989.

[3] H D.H.W. Li and J.C. Lam, “Evaluation of lighting performance in office buildings with daylighting controls,” Energy and Buildings, 2001, vol. 33, pp. 793–803.

[4] C. Maxey, “Hybrid solar lighting: fiber optics bring sunlight inside,” Photonics spectra, Issue. 6, 2008.

[5] W. B. Stine and M. Geyer, “Power from the Sun,” 2001, available at: http://www.powerfromthesun.net/book.html.

[6] V. N. Mahajan, Optical Imaging And Aberrations - Part 1 Ray Geometrical Optics.

[7] EN 12464-1 Light and Lighting – Lighting of work places – Part 1: Indoor work places, European standard, 2002.