International Journal of Energy and Power Engineering
2016; 5(2): 60-66
http://www.sciencepublishinggroup.com/j/ijepe
doi: 10.11648/j.ijepe.20160502.15
ISSN: 2326-957X (Print); ISSN: 2326-960X (Online)

Optical Fiber Daylighting System Featuring Alignment-Free

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To cite this article:

Ngoc Hai Vu, Seoyong Shin. Optical Fiber Daylighting System Featuring Alignment-Free. *International Journal of Energy and Power Engineering*. Vol. 5, No. 2, 2016, pp. 60-66. doi: 10.11648/j.ijepe.20160502.15

Received: April 8, 2016; **Accepted**: April 28, 2016; **Published**: May 4, 2016

Abstract: We present a cost-effective optical fiber daylighting system composed of prism and compound parabolic concentrator (P-CPC). Our simulation results demonstrate an optical efficiency of up to 89% when the concentration ratio of the P-CPC is fixed at 100. We have also used a simulation to determine an optimal geometric structure of P-CPCs. Because of the simplicity of the P-CPC structure, a lower-cost mass production process is possible. Our quest for an optimal structure has also shown that P-CPC has high tolerance for input angle of sunlight. The high tolerance allows replacing a highly dual precise active sun-tracking system with a single sun-tracking system as a cost-effective solution. Therefore, our results provide an important breakthrough for the commercialization of optical fiber daylighting systems that are faced with challenges related to high cost.

Keywords: Compound Parabolic Concentrator, Plastic Optical Fiber, Daylighting

1. Introduction

As a type of green energy, solar energy has been attracting increasing attention in recent years. Common ways of harvesting solar energy include photovoltaics (PV), solar thermal, and daylighting [1]. So far, conversion efficiency of solar cell still is challenge and it is difficult to do this with the cost effectiveness necessary to make solar generated electricity a commercial reality. In certain instances, however, solar energy can be made more competitive by applying it directly to the end use [2]. One of the direct applications of solar energy is daylighting. Daylight is used to illuminate building interiors to affect the indoor environment, health, lighting quality, and energy efficiency [3]–[5]. In sustainable buildings, daylighting can provide energy reductions through the use of electric light controls, and it can reduce the dependence on artificial lighting, which cannot fulfill the needs of the human body [6] .

Daylighting involves collecting natural sunlight for interior illumination. For illumination inside buildings, the collected sunlight is typically guided through a duct or a fiber bundle. [2], [6]–[12]. In building integration, one of the most important features of the remote light transportation is the wiring method and the wiring method is expected to be as simple as that of electrical wires[12]. However, the light ducts have their difficulties for wiring so that daylight transportation through optical fibers is considered as the best approach so far [12]. Only optical fibers are suitable for this requirement. Optical fiber daylighting technology is one of the most efficient solutions for the delivery of natural light to a space in a building where daylight is limited. Optical fiber daylighting systems are composed of three main components: the sunlight collector with a sun tracking mechanism, optical fibers, and luminaires that distribute light in the required space. To facilitate coupling with the fiber bundle, an optical concentrator must be used to concentrate the sunlight [1]. Therefore, optical concentrators play a crucial role in harvesting solar energy. Through the research and development of many public and private groups, two basic collector designs have proven to be the most effective and reliable. The first strategy uses optical lenses to refract and concentrate sunlight into optical fibers; the second design captures incoming light by reflection from parabolic mirrors[2], [6]–[10], [12]. However, both designs suffer from the non-uniformity of the light beam over the end-face of the optical fibers, and additional secondary optics are needed to homogenize the sunlight and increase the optical fiber coupling efficiency and the tracking tolerance [11]. Figure 1

(a) shows the typical mechanism for a optical daylighting system using Fresnel lenses. Numerous designs related to the traditional concentrator have been proposed, which can provide a considerable concentration ratio, but requires a sophisticated alignment between primary concentrator, second optics and optical fiber. They also require acuracy dual-axis tracker and typically a large space.

In the field of concentrated solar energy applications, solid dielectric compound parabolic concentrators (CPCs) recently have been one of the best choices because of simple structure and high efficiency. A solid dielectric CPC concentrates light via reflection and refraction by incorporating a solid dielectric refractive material into the CPC structure as shown in Figure 1 (b). The total internal reflection within the the solid CPC has a high reflectance and therefore may lead to a higher optical efficiency. Mallick et al. [13], [14] have investigated an asymmetric CPC consisting of two different parabolas using a transparent dielectric material. Winston et al. [15]–[17] stated that a solid dielectric CPC has an increased angular acceptance and reduced optical loss compared with its non-dielectric counterpart. However, important characteristics the solid diectric CPC are low concentration ratio and the very high non-homogeneity in the spatial flux distribution produced at the exit aperture. These features is not suite for optcial fiber daylighting system that requires high concentration ratio and uniformly irradiation at exit aperture for optical fiber coupling.

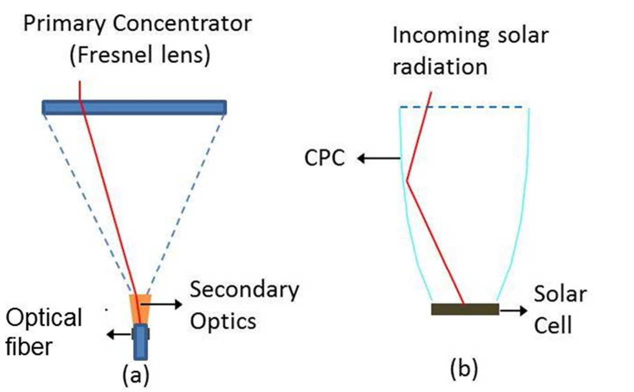

Figure 1. Physical layout of (a) one optical fiber daylighting system using Fresnel lens and (b) a solid dielectric CPC using for CPV applications.

In this study, we introduce an optical fiber daylighting system using a combination of prism and solid dielectric CPC which can achieve high concentration ratio and uniform distribution of solar irradiation inside the optical fibers. This proposed system remains some advantages of CPCs such as low fabrication cost, alignment-free, thus facilitates the viable commercialization of cost effective mass-produced systems. To our knowledge, the optical fiber daylighting system using prism-CPC combination described in this study is the first system that can show cost effective potential when manufactured in volume.

The remainder of the paper is organized in the following manner: Section 2 describes the design concept and model principle of daylighting systems using combination of prism solid dielectric CPC (P-CPC). A detailed description of optical fiber coupling is also discussed in this part. In Section 3, the optical fiber daylighting system based on P-CPC is modeled in LightTools™ software (Synopsys Inc., California, USA) to evaluate the performance of such a system. We also optimize all of parameters that affect on the optical efficiency and angular tolerence of system. Finally, brief concluding remarks and possibilities for future work are included in Section 4.

2. Design Concept and Model Principle

This part introduces the conceptual design and working principle of a combination of Prism-compound parabolic concentrator (P-CPC). The foundation of idea is based on a CPC that was used for many different applications, ranging from high-energy physics to solar energy collection. To modify the CPCs for our purpose, we recall the theory of conventional CPCs. A symmetrical CPC as shown in Figure 2 (a) consists of two identical parabolic reflectors that funnel radiation from the aperture to the absorber [18]. The right-hand side and the left-hand side parabolas are axisymmetric. The focuses of two parabolas form the base of the CPC, as shown in Figure 2 (b). When a sun ray beam is parallel to the main axis of parabolic rim, it will be focused on the focus of parabola as illustrated in Figure 2 (c). A solid dielectric CPC is filled with dielectric materials such as poly-methyl methacrylate (PMMA) [19]. When the incidence angles of the incoming rays are smaller than acceptance angle, the rays would undergo total internal reflection or mirror reflection to reach the base of CPC [17].

In this study, we propose a new aspect of using solid dielectric CPC that utilize the imaging optics property of CPC - a non-imaging optics device. Figure 3 (a) shows the physical layout of our proposed solar concentration device based on combination of prism-CPC. The prism is placed at the top of CPC which can change the direction of incoming solar ray. With appropriate prism angle, the direct sunlight refracts at two edge of prism and divided in two separate beams that are parallel to the axe of 2 parabolic rim of CPC. After reflection at the wall of CPC two beams focus at focal point of parabola as shown in Figure 3 (b).

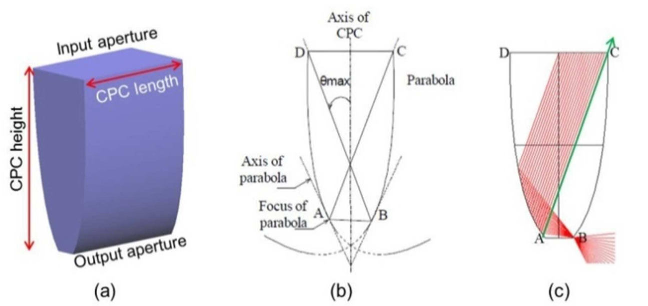

Figure 2. (a) 3D view of a solid dielectric CPC; (b) A symmetrical CPC with parameters and (b) ray tracing of sunlight beam that parallel to axis of parabolic rim.

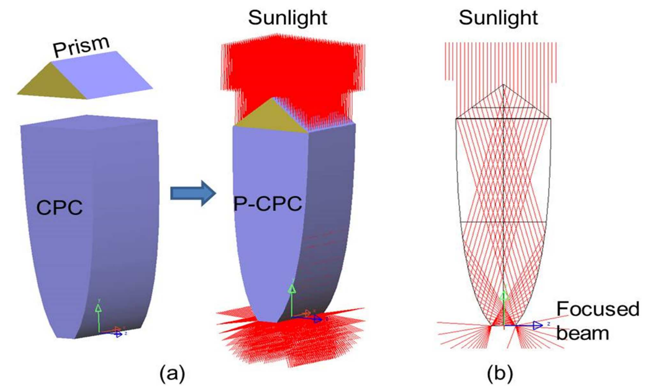

Figure 3. *(a) Physical layout of P-CPC and (b) mechanism of sunlight concentration by ray tracing.*

Figure 4 shows the method to calculate the structrure of prism based on accepctane angle of CPC. The incident angle Θ_i of sunlight ray at the edge of prism is equal to angle α of prism ($\Theta_i = \alpha$). The refracted ray should have direction of parabolic rim of CPC (acceptance angle of CPC: Θ_{acc}). Base on Snells law, the relation between Θ_i and Θ_{acc} is shown in Equation 1.

$$\sin\Theta_{\mathrm{i}} = n_1 \sin(\theta_{\mathrm{i}} - \theta_{\mathrm{acc}}) \quad (1)$$

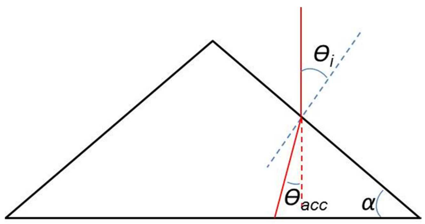

Figure 4. *The relation between prism structure and acceptance angle of CPC.*

The optical fiber consists of a core, cladding, and an external protective coating. The light travels inside the core, while the cladding, which has a lower refractive index, provides internal reflection at the boundary of the core. The optical fibers used in daylighting and solar thermal applications for the transmission of sunlight need to transmit a broad spectrum. One of the most significant features of sunlight transportation is the wiring, and the wiring must be as simple as electrical wiring. Therefore, only optical fibers can fulfill this requirement. Optical fibers were utilized to deliver sunlight to the interior with small losses. Silica optical fibers (SOFs) are known to be good light-transmission media and have the best resistance to heating; however, SOFs are expensive. Plastic optical fibers (POFs) have substantially higher attenuation coefficients than SOFs, but POFs are preferred in daylighting systems due to their lower cost, tighter minimum bend radius, ease of installation and durability for complex wiring in buildings [3], [20]. The light can be transferred over long distances without visible changing of the input color because the POFs are made with PMMA, which has attenuation minima of 64, 73 and 130 dB/km, occurring at 520, 570 and 650 nm, respectively. These wavelengths indicate that the PMMA fibers will transmit green, yellow and red light particularly well. The POF parameters are listed in Table 1.

Table 1. *POF parameters for design and simulation.*

Parameters	
Attenuation	0.45 dB/m
Core/Cladding Diameter	1.960/2.0 mm
Refractive Index: Core/Cladding	1.492/1.402
Minimum Bend Radius	50 mm
Spectral Trans. Range	380–750 nm

The exit port from the P-CPC concentrator has a rectangular shape, so a ribbon configuration of optical fiber is proposed for the optical fiber coupling. We remove apart of optical fiber ribbon and connects to P-CPC by a index matching gel as describe in Fig. 5. (a,b). The light propagates by reflection in POFs to reach the interior for illumination. Fig. 5 (c) shows the optical fiber coupling mechanism using ray tracing method. Rays that exceed the critical angle, as defined by Snell's law, propagate via total internal reflection (TIR) within the waveguide to the exit aperture. Otherwise it will be gone out as loss. For proposed system, the effective sunlight collecting area is calculated by product of CPC length and input size *D*. The output are two end faces of POF. Therefore, the geometric concentration ratio of system C_R as shown in Equation 2. For simply, C_R is ratio of CPC width and POF diameter.

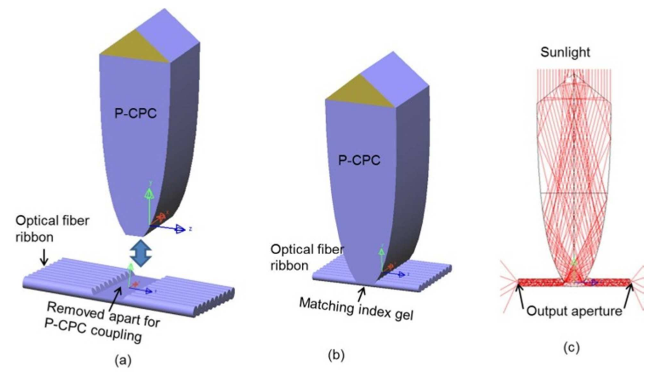

Figure 5. *(a) Optical fibers arranged in ribbon configuration and removed apart for coupling purpose (b) Physical layout of P-CPC coupled with optical fiber ribbon; (b) ray tracing analysis.*

$$C_R = \frac{CPC\ length \times CPC\ width}{Total\ area\ of\ POF\ endfaces} = \frac{D}{2d} \quad (2)$$

The design of daylighting system powered by renewable solar energy was presented in this section. The sunlight concentrator researched in this study is composed of a prism, CPC. The concentrator is supposed to be equipped with a tracking system to collect sunlight in the normal direction [4]. A ribbon optical fiber is attached at the output aperture of CPC to collect the focused sunlight beams. The components of the optical system, design parameters and their effects on the optical performance are discussed in more detail in following section.

3. Optical Analysis and Performance

Optical modelling plays a crucial role in the efficiency evaluation of an optical system. Commercial optical modeling software, LightTools™, was used to design and simulate the geometrical structure of daylighting system based on P-CPC [21]. In the designed system, one of the most common optical plastic, poly-methyl methacrylate (PMMA) with refractive index of n_{PMMA} = 1.518 is selected for prism, CPC and POFs[11]. To evaluate the losses in the system, in simulation model, we inserted three luminous flux receivers as shown in Figure 6.

The optical efficiency, which is simply defined as the ratio of the output luminous flux to the input luminous flux, is a function of the reflection and absorption losses (Equation 3).

$$\eta = \frac{Flux\ on\ Receiver\ 2 + Flux\ on\ Receiver\ 3}{Flux\ on\ Receiver\ 1} \quad (3)$$

The efficiency of system depends on shape of CPC and system concentration ratio. Section 3.1 and 3.2 will discussed these problems in details.

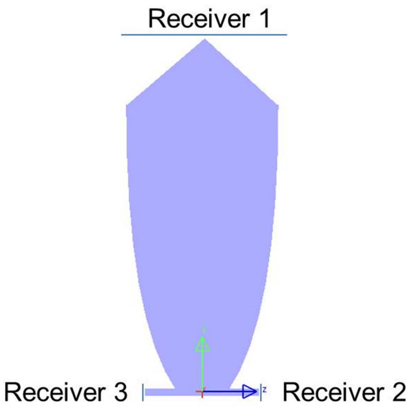

Figure 6. *Illustration of the simulation structure for efficiency analysis.*

3.1. Optimization the Shape of CPC

Loss mechannism is illustrated by ray tracing as shown in Figure 7. The Fresnel reflection losses occur at the boundaries where the light passes from one region to another with different refractive indices. In this proposed system, the Fresnel losses occur at the surface of prism. The Fresnel loss at the conjunction between POFs and waveguide can be reduced to below 0.1% by filling the matching index and then it can be ignored in comparison with other losses. The leak at the parabolic wall of CPC and bottom surface of slab waveguide are also improtant and they can significantly affect the final efficiency of the system. This kind of losses cause by some ray can not satisfy the TIR condition inside the P-CPC concentrator. These losses depend on the shape of CPC. This could be prevented when the solid CPC and slab waveguide has a mirror coating. However the mirror coating usually has a lower reflectance than the total internal reflection, so the coating may have positive or negative effect on the optical performance of a P-CPC.

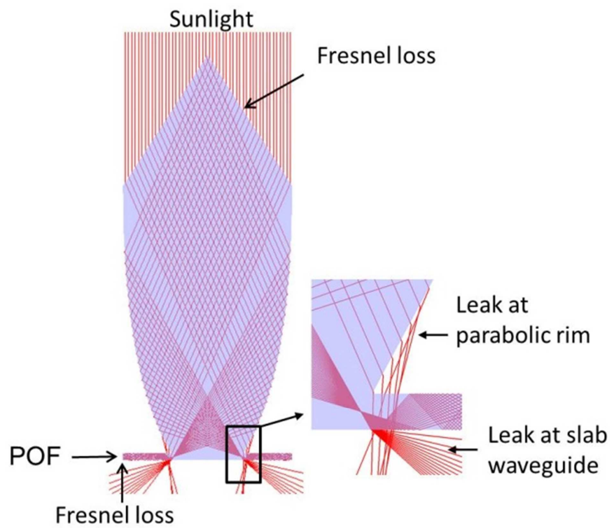

Figure 7. *Losses mechanism of system.*

In order to quantify the effect of CPC shape on the efficiency of the system, a parametric analysis is carried out whilst varying its CPC concentration ratio C_{CPC}. The C_{CPC} is defined by ratio between input apature size and output apature size of CPC. Figure 8 shows the variation of P-CPC concentration system with different C_{CPC}. We fix the input aperture of CPC (input size of system) D = 200 mm. The diameter of POF is fixed at d = 2 mm. Base on Equation 2, the concentration ratio of system archieves C_R = 50.

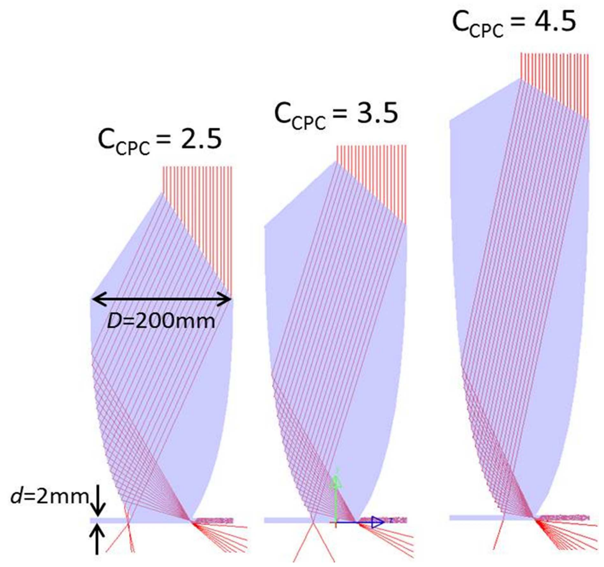

Figure 8. *P-CPC concentration system shape with different shape of CPC.*

To optimization the structure of P-CPC to get highest efficiency, we carried out simulation with several different CPC concentration ratio C_{CPC} in the range of 2 to 8 mm in increments of 0.5 mm. Figure 9 shows that C_{CPC} = 3.5 is the optimal size for structure of CPC to obtain the highest efficiency of 89%.

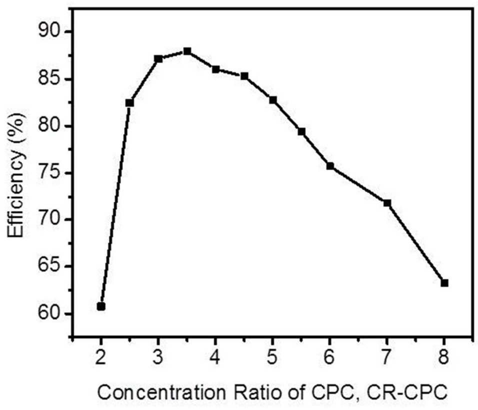

Figure 9. *Variation of optical efficiency at diffirent concentration ratio $C_{R\text{-}CPC}$ of CPC.*

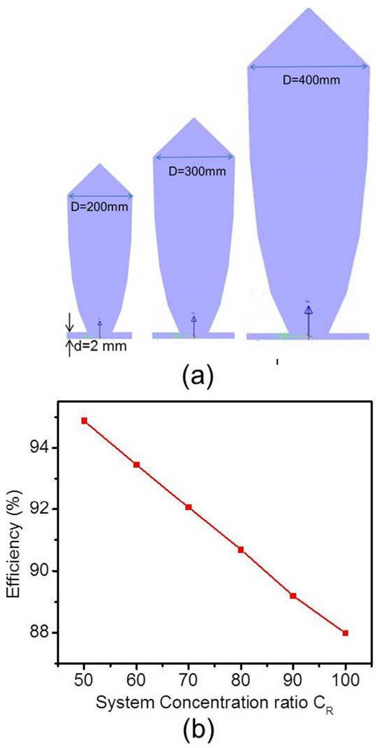

Figure 10. *(a) The variation of P-CPC shape with different concentration ratio C_R. (b) The variation of optical efficiency at different system concentration ratio.*

3.2. The Dependence of Efficiency on the System Concentration ratio C_R

In this proposed system, the prism attached at the top of CPC to direct sunlight beam as shown in Figure 3. However, the prism has an inherent disadvantage that is the dispersion of the solar spectrum. For optical fiber daylighting systems, the dispersion of solar spectrum range is very important since it leads to an essential decrease of the optical efficiency and concentration ratio of the systems. The sunlight is dispersed at the focal point of P-CPC due to the wavelength dependence of refractive index of prism material. The focused area also defines how big the sun image will be at the focal point, and it affect on the coupling between CPC and POFs. Larger core of POFs will capture more focused sunlight but decreases the concentration ratio of system.

We used ray tracing in LightTools^{TM} to analyze the dependence of efficiency on concentration system that is directed by the dispersion phenomanon. The sunlight source used in the analysis is in the range of 300 - 750 nm. POF diameter is fixed at d = 2 mm and P-CPC with input aperture D vary from 200 mm to 400 mm in step of 40 mm. It means the concentration ratio C_R decreases from 100 to 50 in step of 10. Figure 10 (a) illustrates the P-CPC structure with some different input aperture width D = 200 mm, 300 mm, 400 mm, respectively. Figure 10 (b) shows the simulated optical efficiency at different sytem concentration ratio. It can be seen that because of dispersion, system efficiency η is almost linearly decreased with the increase of C_R. The lower concentration ratio can provide higher optical efficiency but also reduce sunlight capturing area.

3.3. Tolerance of the System

For proper operation of the proposed daylighting concentration system, direct sunlight should always be paralle to the main axis of P-CPC. This is a difficult task since the position of the Sun is always changing, and this led us to use a Sun tracking system. The required accuracy of the Sun tracking system is determined by the solar concentrating collector's angle of tolerance [22]–[25]. The tolerance of the system is the acceptable angular deviation of the sunlight direction from the two main axes of the system, within the allowable efficiency loss. It is defined as the angle where the efficiency drops by 10% [26]. The acceptance angle determines the required accuracy of the tracking system mounted upon the concentrator. The dependence of the optical efficiency of the system on angular deviation along the North-South (NS) and East-West (ES) direction are very different because the system is not symmetric. We examined the efficiency with different angular deviations of the sunlight direction along the NS and EW directions. The alignment of system along NS and EW direction was shown in Figure 11.

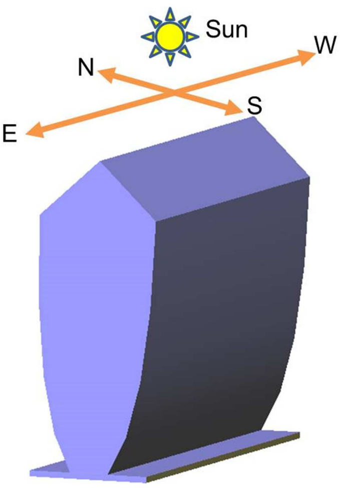

Figure 11. *The alignment of system along NS and EW direction.*

Figure 12 (a) shows the optical efficiency output relative to angular deviation along the EW direction, and Figure 12 (b) shows a graph of effciency versus angular deviation along the NS-direction. The simulation results show that the tolerance is more than ±6 degrees along the EW-direction, which is far larger than that for the EW-direction (±0.5°). This indicates that by using a P-CPC concentrator, the acceptance angle along the EW-direction can be greatly increased without sacrificing too much optical efficiency. Therefore, the proposed system uses P-CPC instead of a conventional lens or parabolic mirror as the concentrator can lower the accuracy requirements along the EW-direction, and this reduces the cost of the tracking system.

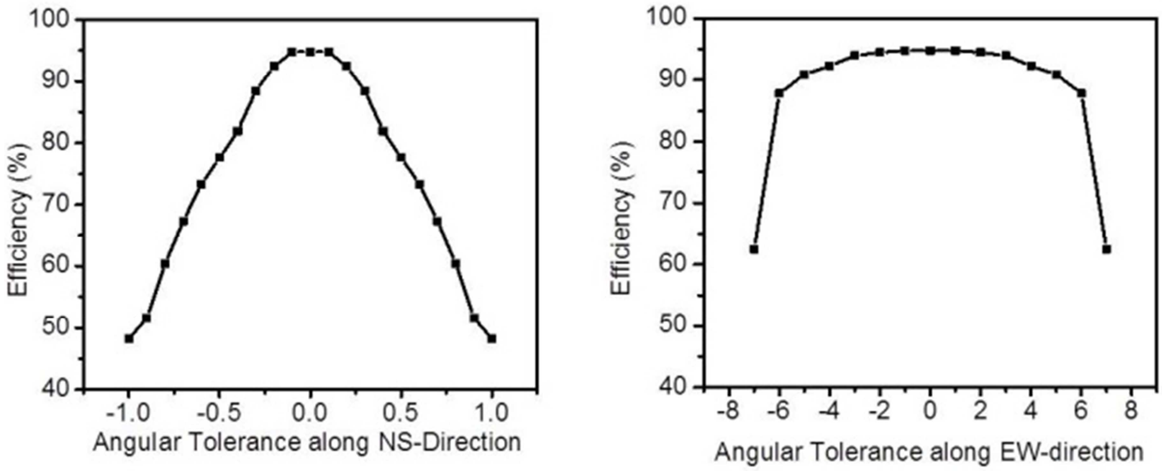

Figure 12. *Variation of optical efficiency of concentrator at different angular deviations along the (a) EW-direction and (b) NS-direction.*

Table 2. *Average illuminance at different times of the day and calculated luminous flux at output for the proposed system.*

Time	**Solar Altitude (°)**	**Sunlight Illuminance (lux)**	**Luminous Flux on the Surface Concentrator (lm)**	**Luminous Flux at the Output of Concentrator (lm)**
6 AM	8	20,000	4000	3800
7 AM	19	40,000	8000	7600
8 AM	31	60,000	12000	11400
9 AM	43	80,000	16000	15200
10 AM	54	100,000	20000	19000
11 AM	65	105,000	21000	19950
12 PM	74	110,000	22000	20900

3.4. Daylighting

The illuminance from the sunlight was measured at different times of the day. The site of application was located at 127° longitude and 37.5° latitude. Here we will look at the illuminance on a summer day as an example: The highest solar elevation (zenith) angle at the site is 76°, and the time is set for 12:30 PM. To achieve direct sunlight, we assume that the daylighting system has a Sun tracking device which rotates the concentrator module toward the Sun all day. The area of the sunlight collector is 0.2 m^2 if we assume that length of P-CPC is 1 m and width is 0.2 m. The measured illuminances of the input flux at the surface of the concentrator and of the luminous flux at the output concentrator are listed in Table 2.

4. Conclusion

An optical fiber daylighting system using P-CPCs has been designed and discussed with the purpose of saving the energy. To explore the practical performance of the proposed system, a sample optical system was modeled and simulated with LightTools™. The simulation results indicate that 89% of optical efficiency was achieved at C_R = 100 for the proposed concentrator system. In addition, the tolerance (acceptance angles) in the NS- and the EW-directions also were analyzed. By using a P-CPC, an acceptance angle of ±6° was achieved in the EW-direction. This allows us to use a lower accuracy sun tracking system, such as a passive Sun tracking system along the EW-direction as a cost effective solution. This study is the first to use a combination of prism and compound parabolic concentrator for an daylighting system. It shows great potential for the commercial and industrial scale daylighting application. In the future, we will try to implement experimentation under real conditions to verifying the accuracy of the simulation and the commercial viability of the system.

Acknowledgements

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2014R1A2A1A11051888).

References

[1] T.-C. Teng and W.-C. Lai, "Planar solar concentrator featuring alignment-free total-internal-reflection collectors and an innovative compound tracker," *Opt. Express*, vol. 22, no. S7, p. A1818, 2014.

[2] M. A. Duguay and R. M. Edgar, "Lighting with sunlight using sun tracking concentrators," *Appl. Opt.*, vol. 16, no. 5, p. 1444, 1977.

[3] I. Ullah and S. Shin, "Highly concentrated optical fiber-based daylighting systems for multi-floor office buildings," *Energy Build.*, vol. 72, pp. 246–261, 2014.

[4] C.-H. Tsuei, W.-S. Sun, and C.-C. Kuo, "Hybrid sunlight/LED illumination and renewable solar energy saving concepts for indoor lighting.," *Opt. Express*, vol. 18 Suppl 4, no. November, pp. A640–A653, 2010.

[5] A. J.-W. Whang, Y.-Y. Chen, S.-H. Yang, P.-H. Pan, K.-H. Chou, Y.-C. Lee, Z.-Y. Lee, C.-A. Chen, and C.-N. Chen, "Natural light illumination system.," *Appl. Opt.*, vol. 49, no. 35, pp. 6789–6801, 2010.

[6] I. Ullah and S. Shin, "Highly concentrated optical fiber-based daylighting systems for multi-floor office buildings," *Energy Build.*, vol. 72, pp. 246–261, 2014.

[7] R. Núñez, I. Antón, and G. Sala, "Hybrid lighting-CPV, a new efficient concept combining illumination with CPV," *AIP Conf. Proc.*, vol. 1477, no. 4, pp. 221–224, 2012.

[8] W. T. Xie, Y. J. Dai, R. Z. Wang, and K. Sumathy, "Concentrated solar energy applications using Fresnel lenses: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 2588–2606, 2011.

[9] H. Abdul-Rahman and C. Wang, "Limitations in current day lighting related solar concentration devices : A critical review," *Int. J. Phys. Sci. Vol.*, vol. 5, no. 18, pp. 2730–2756, 2010.

[10] B. Bouchet and M. Fontoynont, "Day-lighting of underground spaces: Design rules," *Energy Build.*, vol. 23, no. 3, pp. 293–298, 1996.

[11] N. Vu and S. Shin, "A Large Scale Daylighting System Based on a Stepped Thickness Waveguide," *Energies*, vol. 9, no. 2, p. 71, 2016.

[12] E. Ghisi and J. A. Tinker, "Evaluating the potential for energy savings on lighting by integrating fibre optics in buildings," *Build. Environ.*, vol. 41, no. 12, pp. 1611–1621, 2006.

[13] T. K. Mallick and P. C. Eames, "Design and fabrication of low concentrating second generation PRIDE concentrator," *Sol. Energy Mater. Sol. Cells*, vol. 91, no. 7, pp. 597–608, 2007.

[14] T. K. Mallick, P. C. Eames, and B. Norton, "Non-concentrating and asymmetric compound parabolic concentrating building facade integrated photovoltaics: An experimental comparison," *Sol. Energy*, vol. 80, no. 7, pp. 834–849, 2006.

[15] R. Winston, "NONIMAGING OPTICS Limits to Concentration," 2008.

[16] R. Winston and J. M. Gordon, "Planar concentrators near the étendue limit.," *Opt. Lett.*, vol. 30, no. 19, pp. 2617–2619, 2005.

[17] R. Winston and W. Zhang, "Pushing concentration of stationary solar concentrators to the limit," *Opt. Express*, vol. 18, no. 9, pp. A64–72, 2010.

[18] A. Rabl, "Comparison of solar concentrators," *Sol. Energy*, vol. 18, no. 2, pp. 93–111, 1976.

[19] N. B. Goodman, R. Ignatius, L. Wharton, and R. Winston, "Solid-dielectric compound parabolic concentrators: on their use with photovoltaic devices.," *Appl. Opt.*, vol. 15, no. 10, pp. 2434–6, 1976.

[20] H. J. Han, S. B. Riffat, S. H. Lim, and S. J. Oh, "Fiber optic solar lighting: Functional competitiveness and potential," *Sol. Energy*, vol. 94, pp. 86–101, 2013.

[21] O. Selimoglu and R. Turan, "Exploration of the horizontally staggered light guides for high concentration CPV applications," *Opt. Express*, vol. 20, no. 17, p. 19137, 2012.

[22] C. Lee, P. Chou, C. Chiang, and C. Lin, "Sun tracking systems: A review," *Sensors*, vol. 9, no. 5, pp. 3875–90, 2009.

[23] M. T. A. Khan, S. M. S. Tanzil, R. Rahman, and S. M. S. Alam, "Design and construction of an automatic solar tracking system," *ICECE 2010 - 6th Int. Conf. Electr. Comput. Eng.*, no. December, pp. 326–329, 2010.

[24] J. Song, Y. Zhu, Z. Jin, and Y. Yang, "Daylighting system via fibers based on two-stage sun-tracking model," *Sol. Energy*, vol. 108, pp. 331–339, 2014.

[25] H. Mousazadeh, A. Keyhani, A. Javadi, H. Mobli, K. Abrinia, and A. Sharifi, "A review of principle and sun-tracking methods for maximizing solar systems output," *Renew. Sustain. Energy Rev.*, vol. 13, no. 8, pp. 1800–1818, 2009.

[26] P. Xie, H. Lin, Y. Liu, and B. Li, "Total internal reflection-based planar waveguide solar concentrator with symmetric air prisms as couplers," *Opt. Express*, vol. 22, no. S6, p. A1389, 2014.