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Daylighting System Based on Novel Design of Linear Fresnel lens

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Abstract: In this paper, we present a design and optical simulation of a daylighting system using a novel design of linear Fresnel lens, which is constructed based on the conservation of optical path length and edge ray theorem. The linear Fresnel lens can achieve a high uniformity by using a new idea of design in which each groove of the lens distributes sunlight uniformly over the receiver so that the whole lens also uniformly distributes sunlight over the receiver. In this daylighting system, the novel design of linear Fresnel lens significantly improves the uniformity of collector and distributor. Therefore, it can help to improve the performance of the daylighting system. The structure of the linear Fresnel lenses is designed by using Matlab. Then, the structure of lenses is appreciated by ray tracing in LightTools^{TM} to find out the optimum lens shape. In addition, the simulation is performed by using LightTools^{TM} to estimate the efficiency of the daylighting system. The results show that the designed collector can achieve the efficiency of ~80% with the tolerance of ~0.6^0 and the concentration ratio of 340 times, while the designed distributor can reach a high uniformity of >90%.

Keywords: linear Fresnel lens; daylighting system; uniform irradiance distribution; uniform irradiance collector

1. Introduction

Daylighting system is a technology, which allows for collecting and guiding the direct sunlight to the interior dark areas of the building through fiber optics [1–3]. It is one of the branches of renewable energy and it has a significant role to solve the global warming problem by reducing the power consumption for electric light. The power consumption for electric lighting in building occupies a significant part (40–50%) of total energy [4]. Therefore, there are some efforts to reduce the power consumption of electric lighting as using save energy light emitting diode (LED), low energy fluorescent lighting, etc. These efforts help to reduce 10–20% of the energy consumed by lighting [5]. However, that is not good enough for the solution. In addition, the architects try to design the buildings with more windows to get more sunlight. Nevertheless, the light from windows varies according to the position of the sun [6]. Thus, the interior areas are still dark. The artificial light is needed to illuminate these regions.

The previous researches show that the daylighting has two main advantages: reducing the power consumption for lighting and improving the living and working environment for human life [7–9]. A good daylighting system applying for the building can help to reduce the power consumption for lighting by 50–80% [10]. That is a good benefit of the daylighting technology. In terms of human health, using the sunlight in the office building instead of using the artificial light can reduce eye problems by 15%, reduce seasonal affective disorders, and other illnesses. Moreover, the sunlight has positive effects on the human body and improves working environments [11].

Throughout the last two decades, there are many efforts to develop daylighting systems with some different prototypes of this method have been proposed [12–15]; however, just a few of them were commercial. Himawari is the first commercial system, which is developed by a Japan Company [16]. Another commercial daylighting system is Swedish Paran [17]. Both of them have similar principle of operation. They use quartz optical fibers to transfer the sunlight into deeper areas inside of the building. This method helps to reduce the loss of light transition and helps the system overcome the heating problem; however, it makes the system become costly. This is why this technology has not been widely spread in the market so far.

An effective way to reduce the cost of the daylighting system is to use the plastic optical fibers [18–20]. However, the plastic fibers are sensitive to heating problems. Therefore, heat is the main problem, which has to be solved for the daylighting using plastic fibers. The heating problem can be reduced partly if the collector can get a uniform irradiance over one end of the bundle of fiber optics. Nevertheless, the daylighting systems usually use a conventional Fresnel lens, which always creates the hot spot point in the center of the receiver [21–23]. Thus, the daylighting needs to use the secondary lens system to get uniform concentrated light on the bundle of fibers [24,25]. This makes the daylighting system complex in design and costly in manufacture. Therefore, we introduce a novel design of linear Fresnel lens, which can be used to develop the collector and distributor of the daylighting system. In this design, the collector can create the uniform concentrated light on one end of the bundle of fiber optics. In addition, the distributor using this new linear Fresnel lens can distribute the sunlight uniformly over the interior areas of the building.

The daylighting systems just need the visible light to illuminate the interior areas of the buildings. The rest of the sunlight spectrum is wasted, moreover the infrared light contributes to the heating problem and makes that problem more serious. If a concentrator photovoltaic system (CPV) [26–28] is integrated with the daylighting system, the non-visible light can be used to convert to electric power that can be utilized as the light emitting diode (LED) power supply, and the complicated heating problem can be eliminated. This method is useful because the daylighting systems need the LED system to compensate illumination when the daylight is inadequate or not available [18].

In this study, we mainly focus on the design of the collector and the distributor using the new linear Fresnel lens to improve the uniformity. In addition, the methods to overcome the heating problem are presented, leading to the plastic optical fibers that can be used in the daylighting system to reduce the cost. Two daylighting module systems are presented. The first is the daylighting without the CPV system and the second is the daylighting integrated with CPV system. In the first daylighting system, the collector using new linear Fresnel lens directly collects and transfers the sunlight to the bundle of fibers. The heating problem is mitigated partly by uniform irradiance at one end of the bundle of fiber optics. However, this technique is not good enough to solve heating problem. Thus, the bundle of fibers is designed using a combination of glass fibers (SOFs—Silica optical fibers) and the plastic optical fibers (POF). In this design, the short glass fibers, which can operate at high temperature, are used at one end of the fiber bundle that directly receives the concentrated light from the collector. Then, the bundle of plastic fibers is combined to the bundle of glass fibers to transfer sunlight with a longer distance to the interior rooms of the building with cheaper cost. The schematic diagram of the first daylighting system is shown in Figure 1a. In the second daylighting system, the heating problem is solved deeper by adding a plate beam splitter (PBS) to reflect the non-visible light to the CPV solar cells. Therefore, the bundle of fibers is guaranteed to receive the sunlight from the collector without any heating problem. In addition, a bundle of fibers, which is arranged to be a square shape, can match better to the square concentrated light created by the newly designed collector. The schematic diagram of the second daylighting system is shown in Figure 1b.

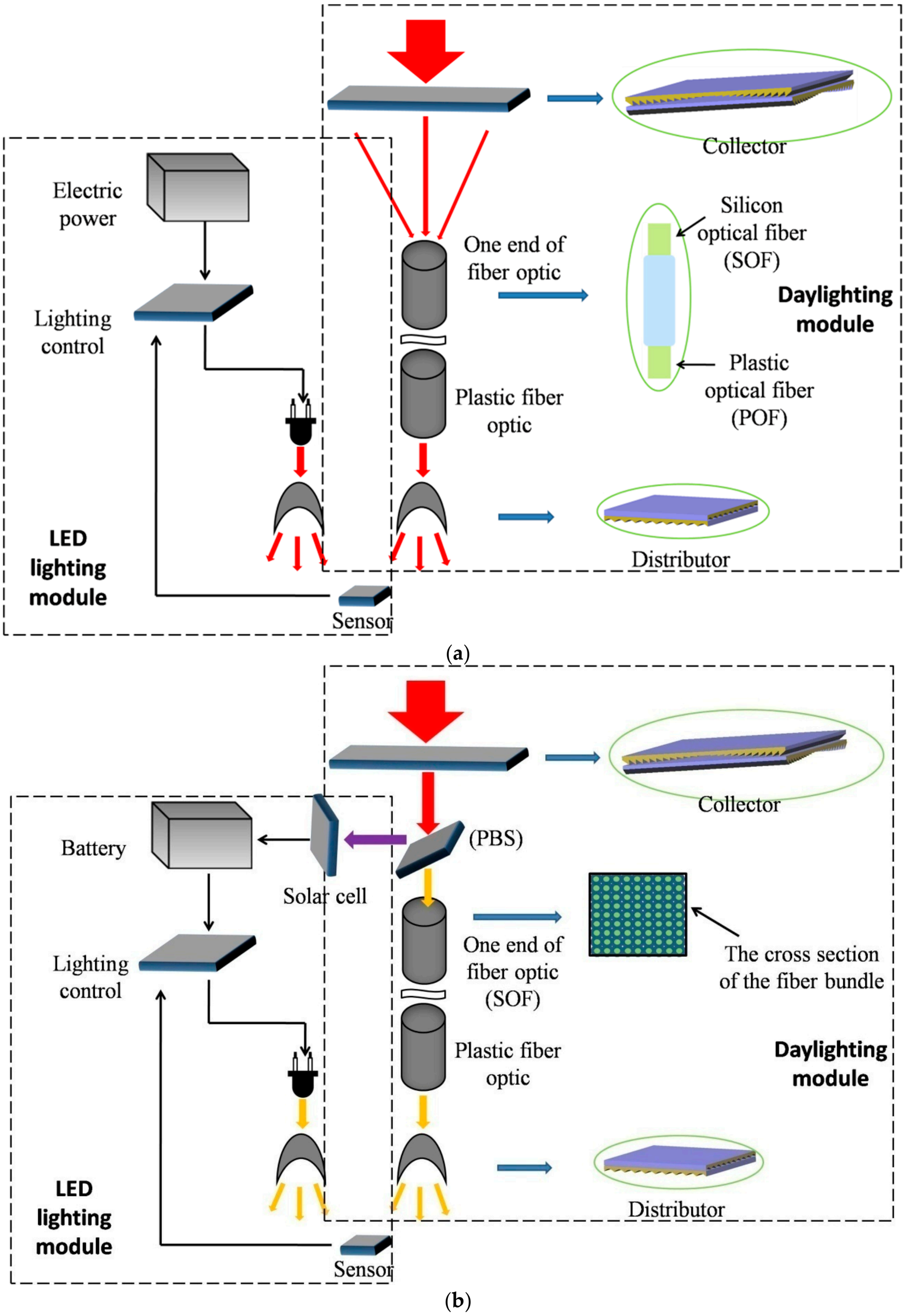


Figure 1. The schemata of the proposed systems. The schema (**a**) is the daylighting system without the solar cells system; The schema (**b**) is the daylighting system integrated with the solar cells system using one plate beam splitter to protect the fiber bundle from the heating problem.

The remainder of the paper is organized in the following manner. In Section 2, the design of the collector using new linear Fresnel lens is indicated. Section 3 describes the structure of the bundle of fibers and heating problem. In Section 4, the distributor structure using new linear Fresnel lens is demonstrated. Section 5 presents the simulation results and discussion. Finally, brief concluding remarks and future work are included in Section 6.

2. Design of Collector

The typical structure of Fresnel lens consists of a series of concentric grooves, which act as individually refracting surfaces to guide the sunlight to a common focal point [22]. In this structure, the Fresnel lens can concentrate the sunlight on two dimensions. That helps to increase easily the concentration ratio of the collector. However, the nature of this Fresnel lens structure always distributes the sunlight over the receiver with non-uniform leading to create a hot spot point in the center of the receiver (in the daylighting system the receiver is the bundle of optical fibers). At the hot spot point, the temperature increases quickly and reaches high value. It can destroy the bundle of the fibers.

The uniformity can be improved if we use the linear Fresnel lens instead of using the Fresnel lens with concentric circular grooves. Nevertheless, the linear Fresnel lens has a small concentration ratio. The lens collects and distributes the sunlight over the focusing line in only one dimension. Therefore, the number of fiber optics has to increase to catch the concentrated sunlight following the focusing line. That makes the cost of the daylighting system increase.

In this design, the collector is built using two linear Fresnel lenses. They are placed perpendicular to each other. With this arrangement, the collector can distribute the sunlight on two dimensions. It helps to increase the concentration ratio and to reduce the required number of optical fibers.

The design of collector is demonstrated in Figure 2. In which, each linear Fresnel lens focuses the sunlight on a focusing line. The first linear Fresnel lens focuses the sunlight on dimension $\vec{Ox}$ as the Figure 3a. While the second linear Fresnel lens focuses the sunlight on dimension $\vec{Oy}$. When the first and second lenses are placed in the same position as the Figure 2, the collector can focus the sunlight on two dimensions with the distribution area being square. In this structure, the grooves of the first lens are perpendicular to the grooves of the second lens. Then, both of the lenses are orthogonal to the direct sunlight to collect the sunlight on two dimensions.

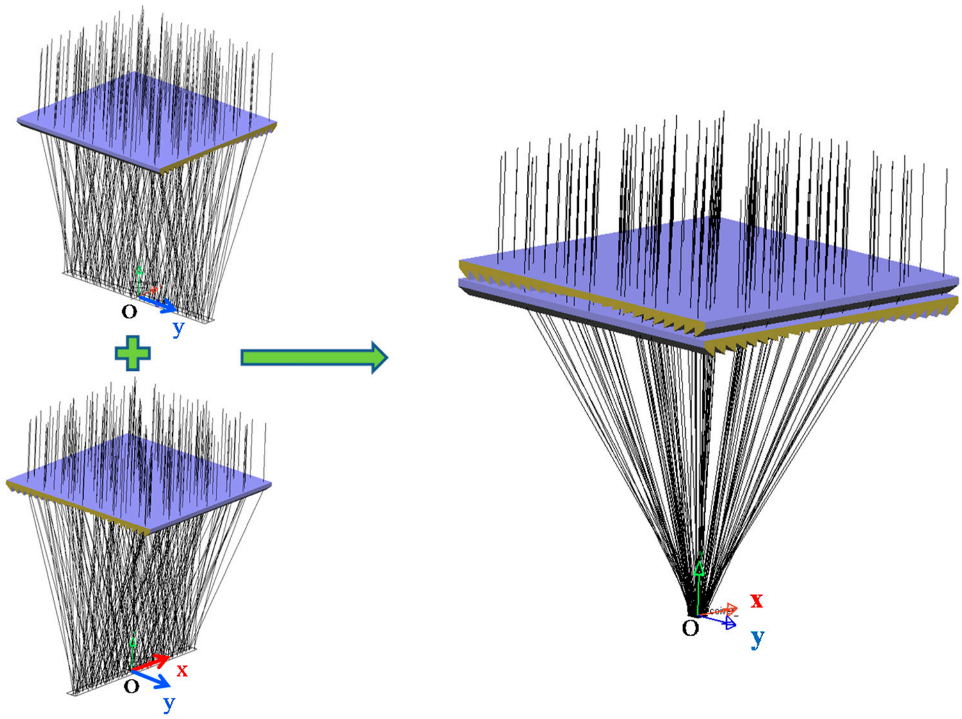
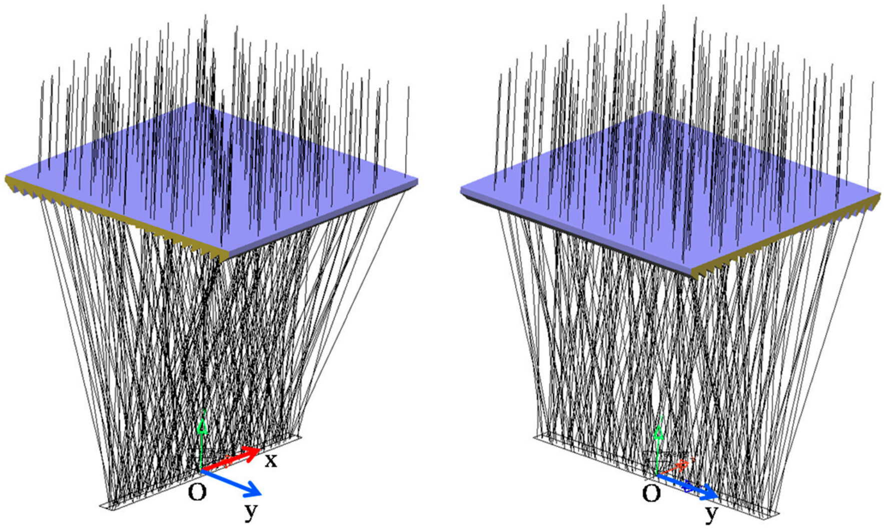


Figure 2. The collector is designed using two linear Fresnel lenses, which are perpendicular to each other and orthogonal to the direct sunlight.

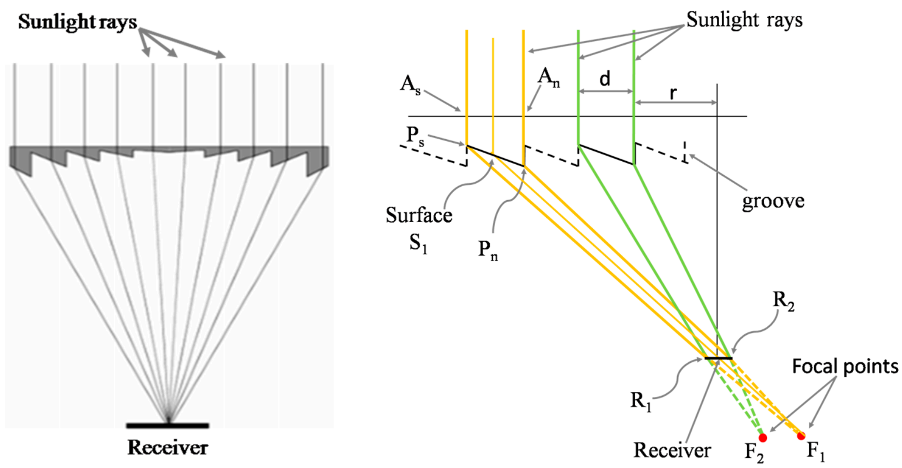


(**a**) (**b**)

Figure 3. The linear Fresnel lenses with (**a**) the linear Fresnel lens focuses the sunlight on dimension $\vec{Ox}$; (**b**) the linear Fresnel lens focuses the sunlight on dimension $\vec{Oy}$.

The collector can achieve a high uniformity when each linear Fresnel lens can create the uniform distribution of the sunlight. The new linear Fresnel lens is designed using multifocal points instead of using only one focal point in the conventional design. In this method, each groove of the new lens has its own focal point. The bundle of sunlight that comes to each groove will be focused to one focal point, which can be the real or unreal point. The edge rays of the bundle of rays come to one groove will go to the extreme points of the receiver while the rays between two edge rays will be distributed somewhere over the receiver.

Figure 4a indicates that the distribution way of conventional linear Fresnel lens, while Figure 4b shows the sunlight distribution of designed linear Fresnel lens.



(**a**) (**b**)

Figure 4. The sunlight distribution by (**a**) conventional Fresnel lens; (**b**) the designed linear Fresnel lens.

The steps in the design procedure for one groove are described as following, with reference to Figure 4b.

Step 1. The designer chooses some initial parameters such as width lens, height lens, width groove, etc.

Step 2. The left edge ray comes to the lens at A_s and then it exits the lens at P_s of the groove. It should go to the extreme point R_1 of the receiver. By this way, the normal of the surface S_1 at P_s can be estimated.

Step 3. The right edge ray comes to the lens at A_n, and then it exits the lens at P_n of the groove. It should go to the extreme point R_2 of the receiver. By this way, the normal of the surface S_1 at P_n can be estimated. The left and right edge rays will intersect each other at the F_1, which is the focal point of the groove.

Step 4. Every ray between two edge rays coming to the groove has the same optical path length with the edge rays. This is expressed as follows

$$nA_sP_s + P_sF_1 = nA_nP_n + P_nF_1 = OPL, \quad (1)$$

where A_sP_s, P_sF_1, A_nP_n, P_nF_1 are parts of optical path length of the left and right edge rays. While n is the refractive index of the lens and OPL is the optical path length constant.

Every point of the S_1 surface between two edge rays can be calculated by using Equation (1). Therefore, the groove of the Fresnel lens can be built successfully.

Step 5. When the design process for one groove has completed, the same procedure is repeated to build the next groove. The point P_n will be P_s in the new process.

By this way, every groove of the linear Fresnel lens is constructed with the exit surface (output surface S_1) is a Cartesian surface, and the limited points of each groove are A_s, A_n, P_s, P_n.

Summary, in this part, we introduced in detail of the collector design of the daylighting system using two designed linear Fresnel lenses. In which the grooves of two lenses are placed perpendicular and orthogonal to the direct sunlight.

3. Structure of the Optical Fiber Bundle and Heating Problem

In daylighting technology, there are some techniques to transfer sunlight from the collector to interior areas of building, such as using pipeline, reflector lens system, fiber optics, etc. [29–31]. In these techniques, the fiber optics is most common by its flexibility. The daylighting system using fiber optics can be designed much easier than that of others. The fiber optics transfer the sunlight inside its core based on total internal reflection (TIR), which happened by the difference of refractive indices between cladding and core ($n_{core} > n_{clad}$). The optical fibers can be glass optical fibers (SOFs) or plastic optical fibers (POFs). The SOFs usually have a small diameter around 2 mm to prevent that they can be broken when they are bent, while the POFs have many dimensions from few mm to cm. If we do not pay attention about the price then the SOFs are a good choice for the daylighting system because they can operate under high temperature and they have a low optical loss. However, the high cost prevents the SOFs become a common choice for the daylighting system. In contrast, even though POFs have a higher optical loss than that of SOFs, they are still a favorite choice for the daylighting system by their cheap price.

In the daylighting systems using POFs, the heating problem is the main challenge. To overcome that problem, engineers usually design the secondary lens system for the daylighting system [24]. Besides that technique, another technique using a combination between SOFs and POFs has been proposed so far. The detail is presented in a research of Irfan Ullah and Seoyong Shin (2014) [10]. In this technique, the SOFs bundle connects to the POFs bundle by using a matching gel to reduce optical loss. The SOFs receive directly the sunlight from Fresnel lens, and then the sunlight is transferred to POFs bundle to guide to the interior areas of the building. This technique is suitable for the daylighting module in Figure 1a.

In this study, the collector using the novel linear Fresnel lens can distribute the sunlight into a square area. Therefore, a square bundle of fibers using a combination of SOFs and POFs is proposed to match well with concentrated light to reduce optical coupling loss. The SOFs bundle consists of eighty-one glass fibers with a diameter of 1.8 mm as Figure 5a, while the POFs bundle consists of eighty-one plastic fibers with diameter 2.0 mm as Figure 5b. Each plastic fiber is connected to each glass fiber by matching gel, and a connector is used to keep the connecting area stable. The bundle consisting of small fibers (1.8 mm) transfers the light to the bundle consisting of large fibers (2.0 mm) help to reduce the optical loss. In addition, the matching gel is used to connect SOFs and POFs bundles, and also help to reduce the optical loss. The bundle of fibers is shown in Figure 6.

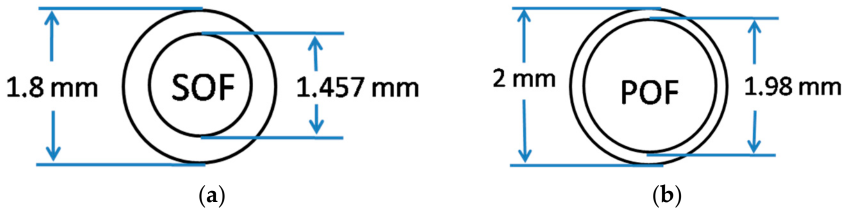


Figure 5. The dimensions of (**a**) glass optical fibers; (**b**) plastic optical fibers.

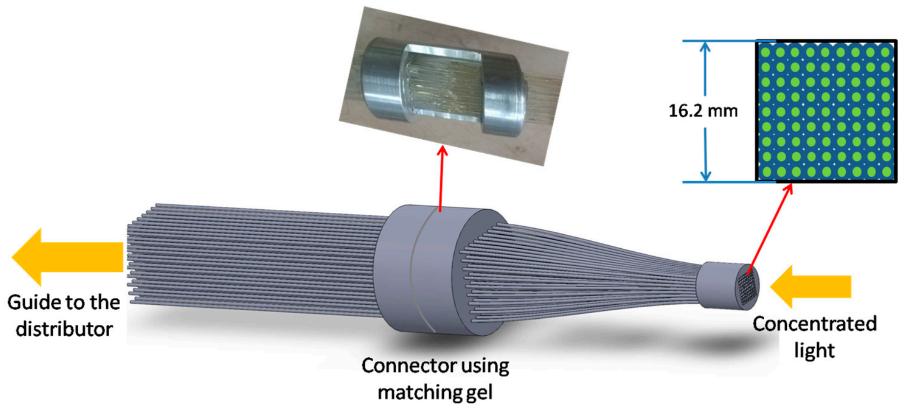


Figure 6. The structure of the bundle using a combination of silica optical fibers (SOFs) bundle and plastic optical fibers (POFs) bundle in which they are connected together by connector using matching gel.

The technique using a combination of SOFs and POFs is a way to solve the heating problem. In addition, this technique also helps to reduce the daylighting system cost by using POFs to transfer the sunlight. Furthermore, the heating problem can be solved in deeper way by using the plate beam splitter (PBS). A PBS is placed in front of the fiber bundle to reflect the non-visible light to the multi-junction solar cells. This technique helps to solve the heating problem and utilize the non-visible sunlight to convert to the electric power applying for the LED system. The PBS is a lens with multi-layer dielectric coating optimized to be able to transmit greater than 85% the visible light and reflect greater than 90% IR wavelength. Figure 7 shows the transmission and reflection of PBS, depending on the wavelength. A PBS from Edmund Optic Inc. (Barrington, NJ, USA) [32] is a choice, which is suitable for the daylighting module that is shown as the Figure 1b.

In the second module, as depicted in Figure 1b, the daylighting system using a combination of SOFs and POFs, plate beam splitter, and newly designed collector is a good structure to solve the heating problem. The collector using new linear Fresnel lens provides a uniform concentrated light. That helps to solve partly of the heating problem. The PBS reflecting the non-visible light to the multi-solar cells also helps to partly solve the heating problem. The combination of SOFs and POFs guarantees that the fiber bundle can receive the concentrated light without any heating problem. Furthermore, in this part, we proposed the configuration of the fiber bundle consisting of eighty-one of SOFs and POFs, in which the SOFs are arranged to the square shape that is suitable for the daylighting system using new structure of collector. A square bundle of fibers matches well to square concentrated light that helps to reduce coupling loss. A combination of SOFs and POFs helps to reduce the system cost.

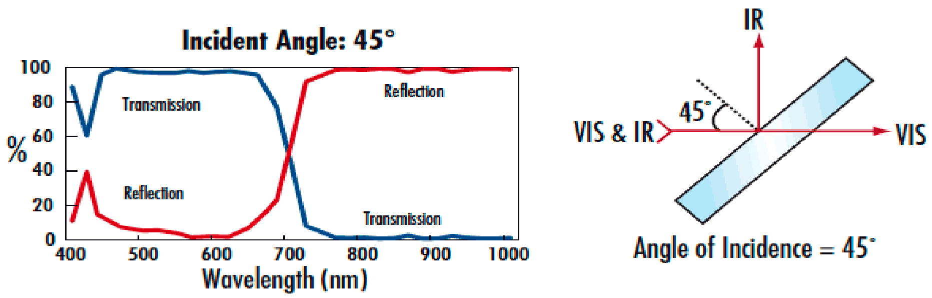


Figure 7. The transmission and reflection depend on the wavelength of plate beam splitter (PBS), which comes from Edmund Optic Inc. (Barrington, NJ, USA) [32].

4. Design of Distributor

In this study, the distributor is designed based on the method, which is similar to the method of design for the collector. The distributor is built by using two new linear Fresnel lenses. However, in this case, the linear Fresnel lenses are divergent lenses instead of convergent lenses used in the collector. The primary components to construct the distributor are divergent Fresnel lenses.

The divergent Fresnel lens is designed based on the conservation of optical path length, i.e., edge ray theorem, and Snell's law. In this design, the essential idea to distribute sunlight uniformly is that every groove of the lens has its own single focal point. Each groove of the linear Fresnel lens has to distribute the sunlight uniformly over the receiver so that the whole lens also distributes the sunlight uniformly all over the receiver. Furthermore, the receiver is huge when compared to the distributor, the focal point of each groove is an unreal point and it is somewhere above the groove.

Figure 8 shows the distribution way for the designed divergent Fresnel lens. In which the bundle of sunlight comes to one groove will be refracted and distributed uniformly over the receiver. The extended parts of refracted rays will be focused to the unreal focal point of the groove.

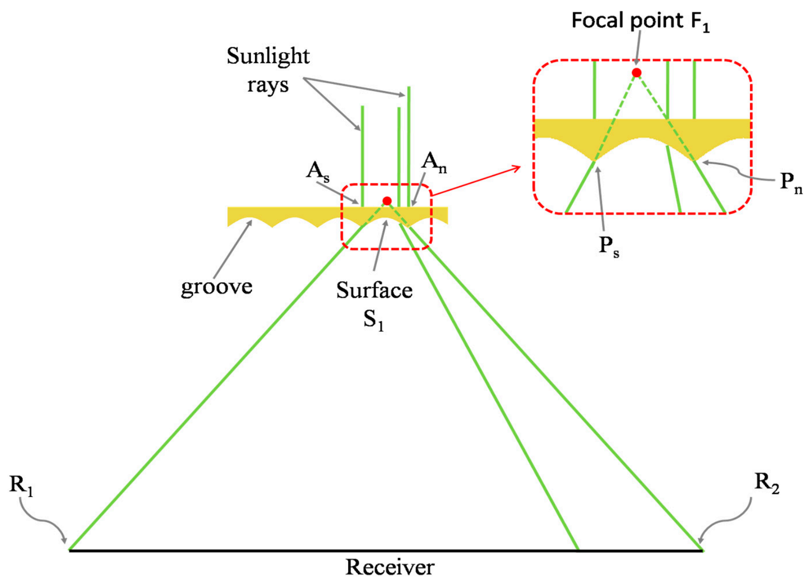


Figure 8. The sunlight distribution by the divergence linear Fresnel lens.

The steps in the design procedure for one groove are described as following, with reference to Figure 8.

Step 1. The designer chooses some initial parameters such as width lens, height lens, width groove, etc.

Step 2. The left edge ray comes to the lens at A_s then it goes to P_s of the groove. At P_s point, it is refracted to go to the extreme point R_1 of the receiver. By this way, the normal of the surface S_1 at P_s can be estimated.

Step 3. The right edge ray comes to the lens at A_n then it goes to the P_n of the groove. At that point, the right edge ray is refracted to go to the extreme point R_2 of the receiver. By this way, the normal of the surface S_1 at P_n can be estimated. Two refracted edge rays will intersect each other at the unreal focal point F_1 above of groove, as depicted in Figure 8.

Step 4. Every ray between two edge rays coming to the groove has the same optical path length with the edge rays. This is expressed as follows

$$nA_sP_s - P_sF_1 = nA_nP_n - P_nF_1 = OPL, \quad (2)$$

where A_sP_s, P_sF_1, A_nP_n, P_nF_1 are parts of optical path length of the left and right edge rays. While n is the refractive index of the lens and OPL is the optical path length constant. In this case, the focal point is unreal and it is above the groove, thus, the optical path length is calculated by subtraction of two parts of optical path length as the Equation (2) instead of the Equation (1) of collector design.

Every point of the S_1 surface between two edge rays can be calculated by using Equation (2). Therefore, the exit surface S_1 can be estimated leading to the groove of the Fresnel lens can be built successfully.

Step 5. When the design process for one groove has been completed, the same procedure is repeated to build the next groove. The point P_n will be P_s in the new process.

By this way, each groove of the linear Fresnel lens is constructed with the exit surface, S_1, is a Cartesian surface, and the limitation points of each groove are A_s, A_n, P_s, P_n.

One divergent linear Fresnel lens can distribute the sunlight on only one dimension. However, a distributor that is a combination of two divergent linear Fresnel lenses can distribute the sunlight on two dimensions. In Figure 9, the first lens with grooves along dimension $\overrightarrow{Ox}$ distributes the sunlight on dimension $\overrightarrow{Oy}$, as shown in Figure 9a, while the second lens with grooves along dimension $\overrightarrow{Oy}$ distributes the sunlight on dimension $\overrightarrow{Ox}$, as illustrated in Figure 9b. Then, they are placed perpendicular to each other and orthogonal to the sunlight to build the distributor. By this way, the sunlight can be distributed in two dimensions, as shown in Figure 10, which shows the distributor using two divergent linear Fresnel lenses.

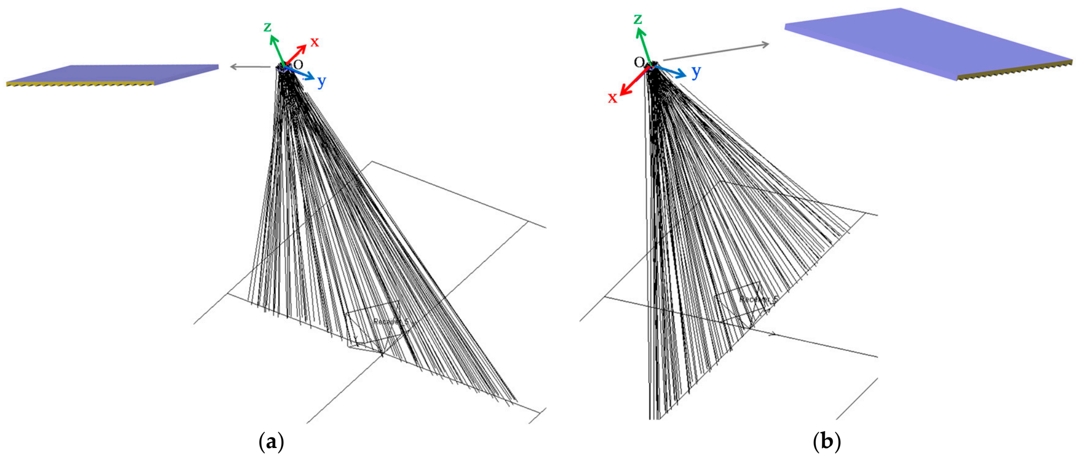


Figure 9. The divergent linear Fresnel lenses distribute the sunlight on one dimension with (**a**) the lens with the grooves along $\overrightarrow{Ox}$; (**b**) the lens with the grooves along $\overrightarrow{Oy}$.

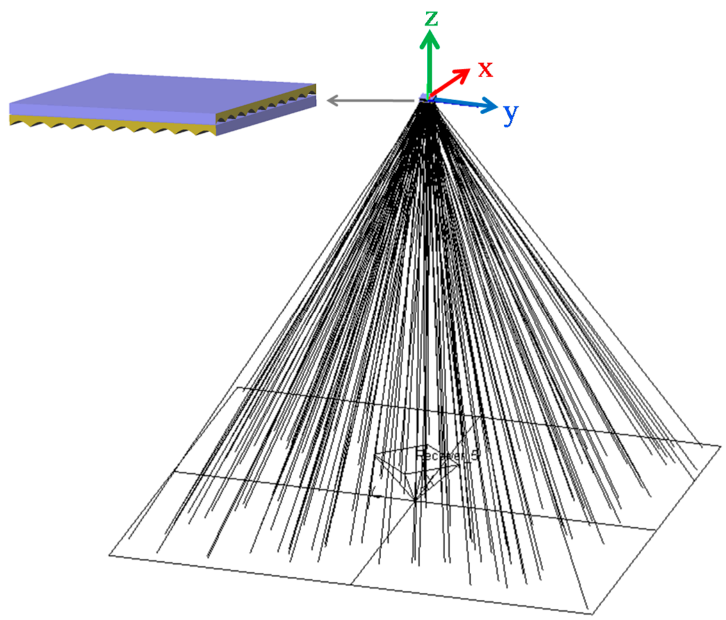


Figure 10. The distributor using two divergent linear Fresnel lenses distributes the sunlight on two dimensions.

Shortly, in this part, the method to design distributor based on two divergent linear Fresnel lenses has been presented. The design of the divergent lens is similar to the design of the convergent Fresnel lens in the second part. However, in this case, the receiver size is much greater than that of the lens, thus, the focal point of each groove is unreal point and it is somewhere above the groove. Therefore, the equation for optical conservation has to be modified to be suitable for the design of the contributor.

5. Performance and Discussion

In this study, we focus on the description of the design of novel linear Fresnel lenses, which are applied to develop new collector and distributor with high performance. From the features of the collector and distributor, the daylighting systems are proposed with the aim of improving the performance and reducing the system cost. In these daylighting systems, the concentration ratio of the collector can be changed easily, while keeping the F_{number}, which is a ratio between the dimension of Fresnel lens and distance from the lens to the receiver (h in Figure 11 and height parameter in Table 1). However, a suitable concentration ratio can protect the fiber bundle and the PBS from the heating problem. As a result, a concentration ratio around 350 times is an acceptable choice. The dimension of convergent linear Fresnel lens is chosen 300 × 300 mm. The collector using linear Fresnel lenses will distribute sunlight onto an area 16.2 × 16.2 mm, where the fiber bundle is placed consisting of eighty-one SOFs with diameter 1.8 mm. With those parameters, the concentration ratio can be calculated as follows

$$C = \left(\frac{D^2}{d^2}\right) = \left(\frac{300^2}{16.2^2}\right) \approx 340, \tag{3}$$

where D is the width of linear Fresnel lens and d is the width of concentrated light. In addition, the F_{number} of the collector can also change easily by this design method. However, it has to be suitable for the numerical aperture of the optical fiber. The numerical aperture of an optical fiber depends on the refractive indices of core and cladding fiber. This is expressed in Equation (4) as follows

$$NA = \sin\theta = \sqrt{n_2^2 - n_1^2}, \tag{4}$$

where NA is the numerical aperture, θ is the angle in Figure 11, n_2 and n_1 are the refractive indices of core and cladding of the fibers, respectively. In this case, the refractive indices Core/Cladding of the glass fibers are 1.457/1.40 leading to the angle $\theta = 23.8^{\circ}$, thus, F_{number} should be greater than 1.134. By these arguments, we can choose the parameters that are suitable for the daylighting system. Tables 1 and 2 show the parameters for the collector and optical fibers applied for the proposed daylighting system.

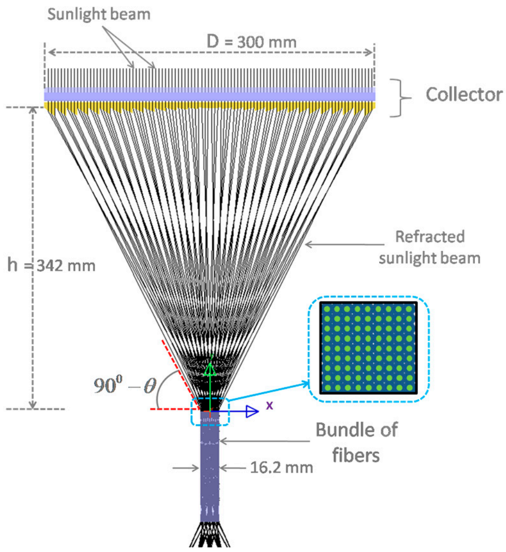


Figure 11. The ray tracing of collector and some parameters of the daylighting system.

Table 1. The parameters of linear Fresnel lens for the collector.

Linear Fresnel lens	Values
Dimension	300 × 300 mm
Height (h in Figure 11)	342 mm
F_{number}	1.134
Groove pitch	10 mm
Number of grooves	30
Material	PMMA (Polymethyl methacrylate)
Thickness	5 mm

Table 2. The parameters of the SOFs and POFs technical specifications.

Optical Fibers	Values
Attenuation for SOFs	4 dB/km
Attenuation for POFs	250 dB/km
SOFs Core/Cladding diameter	1.457/1.8 mm
POF Core/Cladding diameter	1.98/2.0 mm
Refractive indices Core/Cladding of SOFs	1.457/1.40
Refractive indices Core/Cladding of POFs	1.490/1.46

The design process of linear Fresnel lens is performed by Matlab program. Then, the lens shape is drawn in three-dimensional (3D) in LightTools™ software (8.5.0 SR2 version, Synopsys, Inc., Mountain View, CA, USA). The ray tracing technique in LightTools™ is used to estimate the structure of designed collector and distributor. Furthermore, the simulation process is also performed in LightTools™ to find out the optimal structure and optical property of collector and distributor.

Figure 11 shows the ray tracing of the collector. The sunlight beams coming to the collector, which is built by two convergent linear Fresnel lenses, are refracted to go to the bundle of optical fibers. The ray tracing technique indicates that if the selection of dimensions and parameters for components of the daylighting system is good, then it makes the refracted sunlight beams able to catch well to the optical fiber bundle. Furthermore, the uniformity of concentrated light is an important parameter for the daylighting system. Therefore, the simulation of the collector is carried out in Lighttools^{TM} and Figure 12 shows the uniformity of concentrated light, which is created by the designed collector.

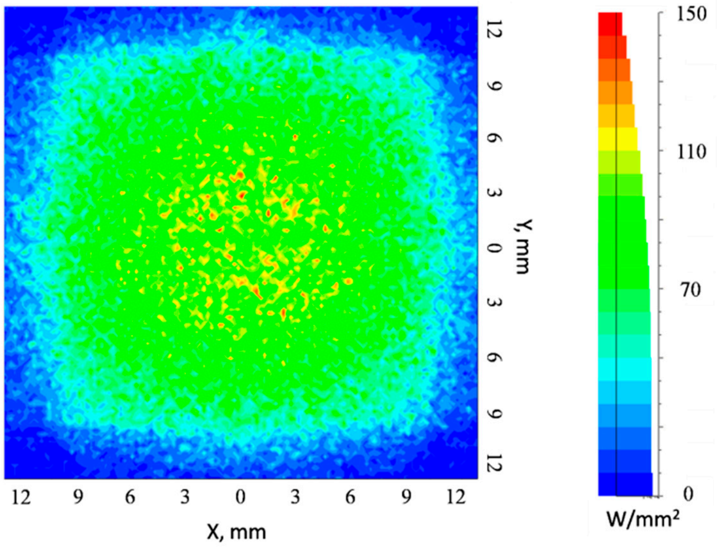


Figure 12. The distribution of concentrated light over the one end of the bundle of optical fibers.

Figure 12 indicated that the distribution of concentrated sunlight is a square area. Therefore, a square bundle of fibers is suitable for this case because the fiber bundle can match to the concentrated light better. In addition, the square concentrated light also matches well to the solar cells in the second module (Figure 1b) of the recommended daylighting systems. Figure 12 demonstrated that the distribution of the sunlight is uniform, which is one of the ways to solve the heating problem besides using PBS, SOFs, and POFs combination, and suitable concentration ratio.

Proper operation of the daylighting system requires direct sunlight to focus into the bundle of fibers. Nevertheless, the position of the sun in the sky changes all the time. Thus, a dual tracking system is recommended for the daylighting system. Even though the tracking system is used for the daylighting system, the tolerance of collector is needed to consider because some errors can exist in the alignment technique, manufacturing process, etc. Therefore, the tolerance (acceptance angle) of the collector using two linear Fresnel lenses is investigated. The acceptance angle is defined as the incident angle of the sunlight at which the solar power over receiver drops to 90% of its maximum [33,34]. Figure 13 shows the tolerance of collector around 0.6^0 of the newly designed collector. It is an acceptable value for the daylighting system.

The optical efficiency is an important parameter for the daylighting system. Therefore, the optical efficiency of the collector is investigated by using LightTools^{TM}. The efficiency of the collector is calculated by the power ratio between the concentrated light and the direct sunlight coming to the lens surface. In this design, the efficiency of the collector can reach up to ~80%. The primary optical loss is Fresnel loss on the surfaces of the lenses. In this case, the collector is a combination of two linear Fresnel lenses so that it makes the Fresnel loss increase. However, the designed daylighting system does not require the secondary lens to get homogeneous irradiance, thus, that efficiency is an acceptable value. On the other hand, the efficiency of the distributor is 81.49%, which is estimated in LightTools^{TM}. This value is similar to the efficiency of the collector because both the collector and distributor are designed by using new linear Fresnel lenses. About the distributor, the uniformity is the most important parameter, which is shown and mentioned in Figure 14.

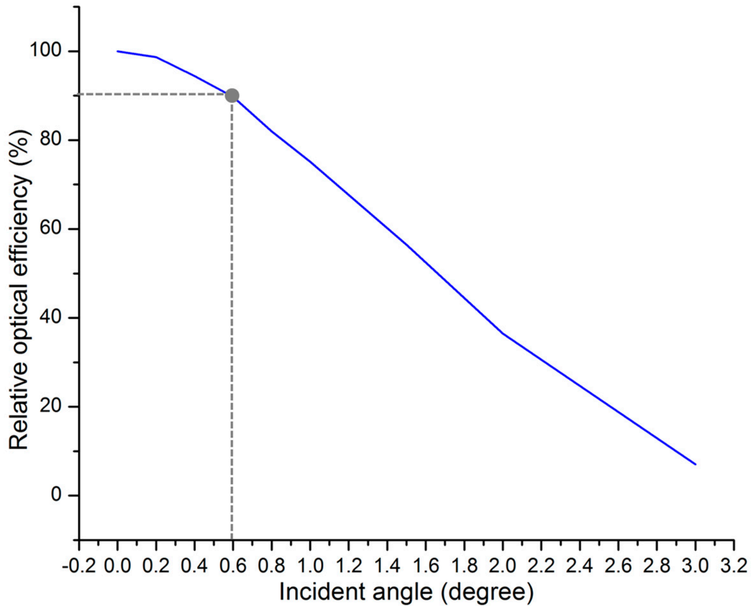


Figure 13. The tolerance of the designed collector.

Moreover, the overall performance and the illuminance at the interior of the proposed daylighting system are calculated. Using the sunlight illuminance (lux), we can calculate the luminous flux on the surface of collector (lm), which is the input power for the daylighting system by using Equation (5) as follows

$$F = E \times S \quad (5)$$

where F is the input luminous flux in lumens, E is the measured illuminance of sunlight, and S is the area of sunlight collector. With the area of a collector, 0.09 m^2 and the measured illuminance of sunlight of 110,000 lux at 12 PM, the luminous flux on the surface collector is 9900 lm. The collector focuses the sunlight into the area of 16.2 $\times$ 16.2 mm, which is the one end of the fiber bundle (consisted of 81 SOFs). However, only the rays coming to the fiber core of optical fiber bundle can be propagated into the interior, so there is an optical loss for coupling. The optical loss of SOFs is negligible so that the optical loss of bundle of fibers consists of connector loss and POFs loss. The optical loss of bundle of fibers with 10 m length is 3 dB (0.5 dB due to connector (as Figure 6) and 2.5 dB due to POFs, which is shown Table 2). Using all of these parameters, the illuminance in the interior is calculated. With the input luminous flux of 9900 lm, the luminous flux in the interior is 1666.61 lm. The efficiency of overall performance is 16.834%. The overall efficiency is small because of natural characteristics of the daylighting system. However, it can provide 83.33% of the required illuminance of a room of 2 $\times$ 2 m. An office area is required to achieve an average illuminance of 500 lux. In this case, the output is 1666.61 lm, which can provide an average 416.653 lux for the room of 2 $\times$ 2 m, it is equal to 83.33% of the required illuminance.

In an office building, the floor-to-floor distance is usually from 3 to 4 m, depending on the area in the world. Therefore, the distance between the working plan and ceiling is around 2–3 m [35]. In this study, a distance from the working plan to a ceiling of 2 m is chosen to estimate the optical properties of the designed distributor. The distributor, using two divergent linear Fresnel lenses, is built and investigated in LightTools^{TM}. The designed distributor with dimension 10 $\times$ 10 mm, height 2 m will distribute sunlight on a working plan 2 $\times$ 2 m. Figure 14 shows that the sunlight distribution on the working plan is uniform. The uniformity can be calculated by the ratio between minimum irradiation and maximum irradiation. The uniformity is perfect if it reaches one (100%).

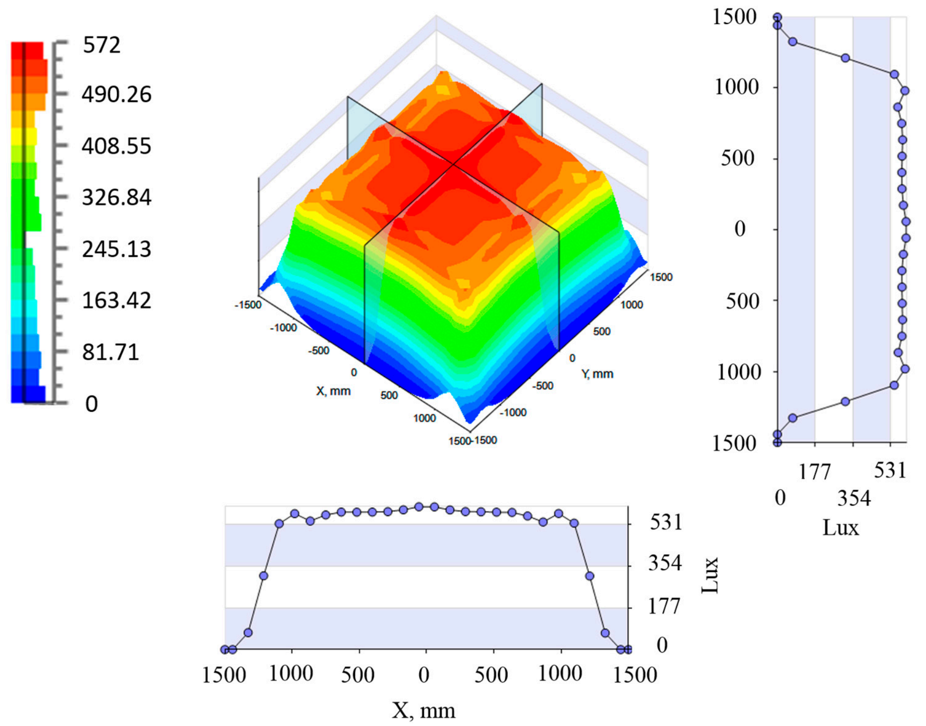


Figure 14. Irradiance distribution of designed distributor on working plan 2 × 2 m.

To investigate the uniformity of the distributor, the light source with power 20 Watts and a wavelength range from 360 nm to 1000 nm, similar to the sunlight is used for simulation. The light source power in Watt unit can be converted to lumen unit. The conversion rate depends on the wavelength or the kind of light source. In this case, the LightTools^{TM} provides the conversion ratio, which is 1 Watt equal 167.3 lumens. Therefore, the light source with power 20 W equals 3346 lumens. Furthermore, the number of rays used for simulation in LightTools^{TM} is 1,000,000 rays for estimation of the uniformity of distributor. The receiver in Figure 14 is divided into 26 × 26 = 676 points to obtain the data from the simulation process of the distributor. The results of simulation show that the minimum irradiance in area 2 × 2 m is 534.2 lux, and that the maximum is 571.2 lux. Therefore, the uniformity of distributor is 93.5% over area 2 × 2 m. It is really a good value for the distributor and it has promising potential for the application of illumination LED technology. Moreover, the results show that the proposed daylighting system with 0.18 m^2 using good illuminance of sunlight provides 100% of the required illuminance of office with uniformity 93.5% over working plan 2 × 2 m.

6. Conclusions

In this study, the design of linear Fresnel lenses, which are convergent linear Fresnel lens and divergent linear Fresnel lens, is presented. The convergent linear Fresnel lens is used to build the collector, while the divergent linear Fresnel lens is applied to construct the distributor of the daylighting system. Both the collector and distributor are developed by using two linear Fresnel lenses. In which, two linear Fresnel lenses are placed perpendicular to each other and orthogonal to input bundle of rays. By this design, the collector can focus and the distributor can distribute the sunlight on two dimensions instead of only one dimension if using one linear Fresnel lens. In addition, the irradiance uniformities, which was created by the collector and distributor, are improved significantly, reaching >90% for the distributor. Based on the features of the collector and distributor, using a new design of linear Fresnel lenses, the daylighting system is proposed to improve performance and reduce system cost. In this system, the heat problem is solved by using four techniques. The first is to use a newly designed collector, which can create uniform concentrated sunlight over the bundle of fibers. The second is to use PBS to reflect the non-visible light to go to multi-junction solar cells. The third is to use the combination of SOFs and POFs, in which the SOFs collect the concentrated light while the POFs is used to transfer the sunlight with effective cost. Finally, the last is to use a suitable concentration ratio of the collector. These techniques help the daylighting system use optical fibers to receive and transfer efficiently sunlight to the interior areas of the building. All of these factors substantially help to construct the daylighting system with high performance and effective cost.

In the future, the prototype of the daylighting system will be built and then the experiments using that prototype can be carried out to check out how the designed daylighting system works. The experiment results will be compared to the simulation results to understand and optimize the daylighting system.

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