Innovative light-collecting module using prismatic array structures

Allen Jong Woei Whang (黄忠偉), Cheng-Ming Chang (張政民)*, Chun-Han Chou (周俊翰), Chia-Min Lin (林家民), Shih-Min Chao (趙世民), Kai-Cyuan Jhan (詹凱全), and Ming Cheng Wang (王明政)

Department of Electronic Engineering, National Taiwan University of Science and Technology, #43, Section 4, Keelung Road, Taipei, 106, China

**Corresponding author: D10202301@mail.ntust.edu.tw*

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Presently, energy conservation and carbon dioxide emission reduction have become increasingly important because of global warming. Using solar energy, which is considered as one of the most important renewable energy sources, does not only decrease the consumption of fossil fuels, but also slows down the pace of global warming. For indoor illumination, our team has developed a technique called "Natural Light Illumination." Instead of using solar cells, our system directly guides sunlight into the interior of a structure. However, the efficiency of the light-collecting module is still low. To address this problem, we propose a new light-collecting module based on a prism array structure with high efficiency. We use optical simulation tools to design and simulate the efficiency of the module, which is found to be 57%. This value is higher than that of the original concentrator (i.e., 11%).

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The issue of environmental protection has been receiving significant attention in recent years. Green energy industries are becoming increasingly important worldwide, particularly in the field of architecture[1]. Energy conservation and carbon dioxide emission reduction are among the most critical issues currently faced by the world. Solar energy is a renewable energy source that can be used widely. One of its possible applications is to illuminate solar cells[2,3] to transform light energy directly into electricity. However, because of their low efficiency and high cost, solar cells are not economically feasible at present. Our team has designed a product that can guide natural light to building interiors for indoor illumination to save energy and create healthy illumination.

A system, called the "natural light illumination system" (NLIS)[4], is thus proposed. The concept for collecting daylight of the NLIS exhibits the benefit of directly using solar energy without losing energy during the transformation of solar energy into electrical energy. The NLIS uses a prismatic unit, called "light-brick" as a concentrator to collect sunlight for indoor illumination without the need for photoelectric conversion. Thus, this system has higher efficiency for illumination.

In this study, a new structure concentrator based on prismatic elements is proposed. The structure has two main parts: the prism array design and the modulation system to decrease Fresnel loss in plastic materials and increase efficiency simultaneously.

The NLIS consists of three sub systems: the light-collecting system, the light-transmitting system, and the light-emitting system (Fig. 1)[5]. Sunlight is collected by the static concentrator and then transmitted through the light pipe. Finally, light is emitted for indoor illumination. The core component in the entire system is the static concentrator, which has been designed based on the light refraction and reflection principles of geometric optics. Moreover, a plastic material is applied on the concentrator because this material is cheaper when commercialization is considered.

The original collecting unit in the NLIS is a cascaded prismatic element called "light-brick"[6], as shown in Fig. 2. The "light-brick" can be regarded as a two-prism

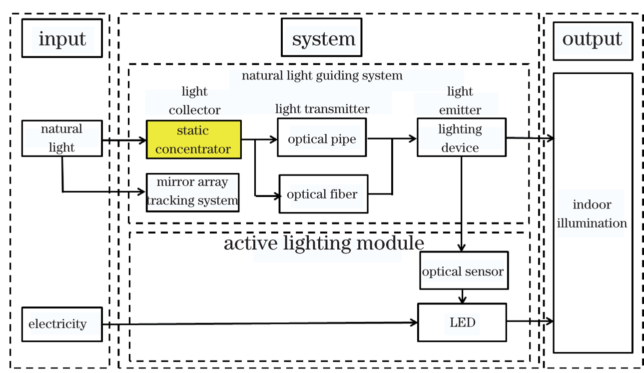

Fig. 1. Structure of the NLIS.

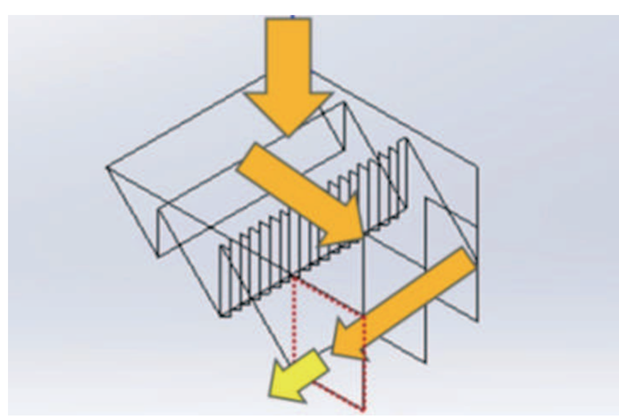

Fig. 2. Sunlight path in the "light-brick".

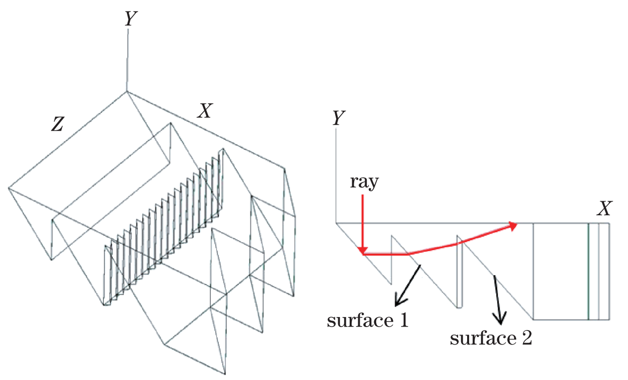

Fig. 3. Three-dimentional (3D) view and the section sharpening of the original "light-brick".

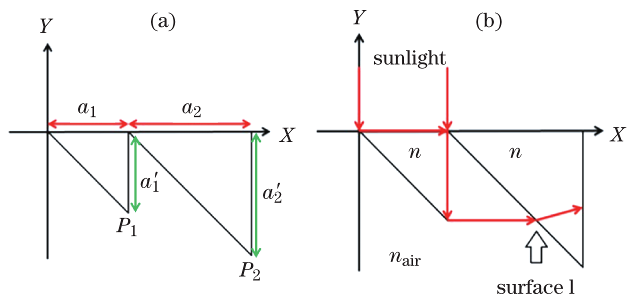

Fig. 4. (a) Basic two prism; (b) ray refraction on surface 1.

array in two different dimensions. The main principle of the "light-brick" is to compress the light source of a large area into a small area. The efficiency of the unit is only 30.33%, which is the ratio of the output power to input power.

Before discussing the new structure, we used a mathematical model and simulation software to analyze the original "light-brick" as shown in Fig. 3. Viewed from the X–Y plane, the "light-brick" experiences refraction and deflects slightly upward on surface 1 when a normal incident ray passes through the first prism[7]. The same situation also occurs on surface 2. Energy loss within the unit can be observed by analysis and by simulation using optical software. The losses mainly originate from two parts: Fresnel loss and ray deflection. Thus, the purpose of our design is to lower such losses as much as possible.

Constructing the mathematical model is necessary to redesign the unit. Starting from the basic element in our research, two right-angle prisms with index n and lengths $a_1$and a_2, where $a_2 > a_1$, were identified (Fig. 4(a)). P_1 and P_2 can then be easily obtained:

$$\begin{cases} P_1 = (a_1, -a_1{}') \\ P_2 = (a_1 + a_2, a_2{}'). \end{cases} \tag{1}$$

According to the edge ray principle and Snell's law (Fig. 4(b)), the light beams deflect an angle θ when passing through surface 1. If another right-angle prism is set directly along the $+X$ direction behind the second prism, as shown in Fig. 5(a), then the light beams will deflect again. When more prisms are set in the prism array, then the angle deflected by the light beams becomes larger. The next prism should be shifted in the $-Y$ direction for a distance s to avoid such situation. As shown in Fig. 5(b),

$$n_{\text{air}}\sin 45° = n\sin\theta, \tag{2}$$

Θ_{s} can be obtained by Snell's law.

$$\begin{cases} \theta = \sin^{-1}\left(\dfrac{n_{\text{air}}\sin 45°}{n}\right), \\ \Theta_{\text{s}} = 45° - \theta \end{cases} \tag{3}$$

where S can be derived according to Eq.(3) and Fig. 5, as follows:

$$S = a_1 - (a_2 - a_1)\tan\theta_{\text{s}}. \tag{4}$$

Similarly, a prism array can be constructed by applying this method. All the input light beams only deflect once at most when passing through the structure. The prism array in the other dimension has the same structure. The entire unit is then constructed, as shown in Fig. 6.

In the NLIS, the efficiency of the original "light-brick" unit is 30.33%. However, the module design of the NLIS decreases the efficiency to 11%. Thus, our main objective is to lower refraction loss and ray deflection in the module design. The material used is PMMA (n=1.4935).

Figure 6 shows the path of the light beams. The incident beams first pass from the $-Y$ to the $+Y$ direction, then through the prism array and to the $+X$ direction, and finally, to the output surface through the other prism array in the $-Z$ direction.

The next step is to add another unit that is rotated around the Y axis at 180°, as shown in Fig. 7.

Based on this structure, we start extending toward the $+Z$ direction. When the second unit is added, it must be shifted by 10 mm toward the $-X$ direction to avoid

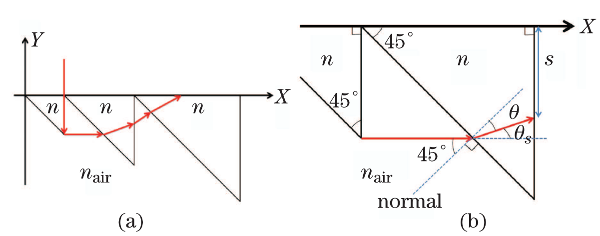

Fig. 5. (a) Ray deflection in the prism array; (b) shifted distance s.

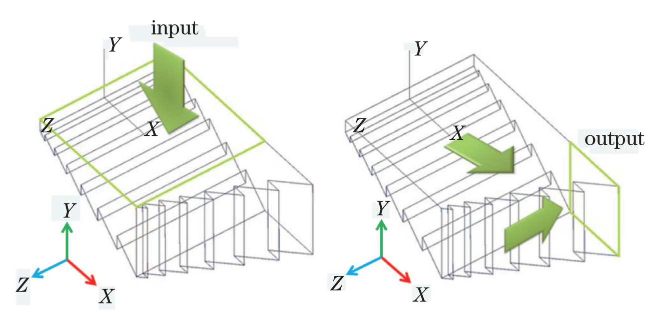

Fig. 6. Paths of the light beams.

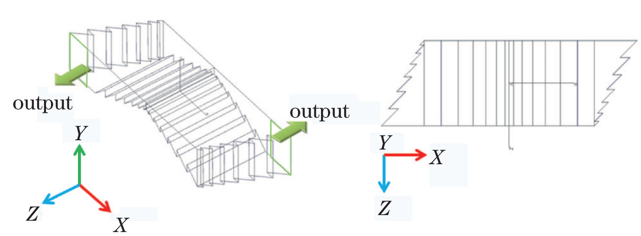

Fig. 7. Design of the two units.

losses caused by ray deflection and refraction.The entire module can be extended by 5 units toward the $+Z$ direction. Based on such design, the module can be extended infinitely toward the $+X$ direction, as shown in Fig. 8.

Ray tracing software TracePro (Lambda Research Corporation, USA) is employed to analyze refraction and reflection of light, and to confirm the design of the new structure. The simulation consists of two parts. We first simulate the efficiency of the unit and the module when normal incident light is applied. We then change the incident light from 0° to 45° to analyze the efficiency of the module in different incident angles. Finally, sunlight data in Taipei from the Central Weather Bureau is employed to simulate the whole day during different seasons to determine the efficiency of a single module.

Normal incident light is applied to the unit with 1W, with an efficiency of 69%. Figure 9 shows the simulation for a module under the same situation, but with an efficiency of 57%.

Then, we change the incident angle of input from 0° to 45° (Fig. 9) and simulate the unit and the module to analyze their efficiencies. The efficiency list is shown in Table 1 and Table 2. Table 1 shows the unit efficiency of a prismatic structure. The maximum efficiency of the unit when the angle of the light source is a right angle to the unit is 69%. Thus, the maximum tolerance angle of the unit is 27°. Table 2 shows the module efficiency. The maximum efficiency is 57%, and thus, the maximum tolerance angle of the module is 10°. We also analyze the reasons of the decline of the efficiency and the maximum tolerance angle. The results show that given that the light path is longer than the unit, the non-collimate light source deflects, and thus, light cannot be transmitted to the output.

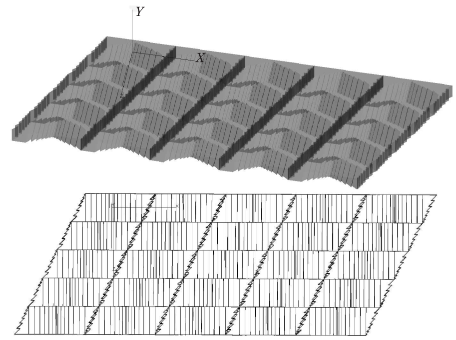

Fig. 8. Extended module.

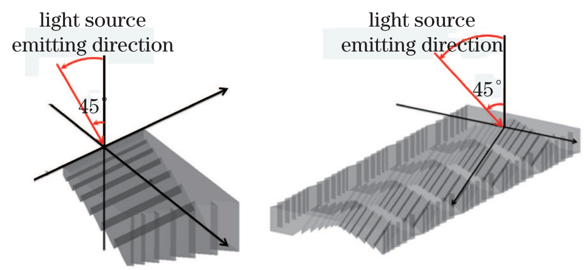

Fig. 9. Change in incident angle during the simulation.

Table 1. Unit Efficiency List with Different Incident Angles

Incident Angle	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°
Efficiency (%)	69	62.71	57.88	52.8	47.18	39.55	28.19	17.4	8.8	5.86

Table 2. Module Efficiency List with Different Incident Angles

Incident Angle	0°	5°	10°	15 °	20°	25°	30°	35°	40°	45°
Efficiency (up) (%)	28.72	21.91	20.15	17.52	14.78	13.15	10.32	6.86	3.3	2.17
Efficiency (down) (%)	28.87	9.46	3.62	2.06	1.16	0.022	0.014	0.007	0.003	0.001
Total (%)	57	31.38	23.78	19.58	15.94	13.17	10.34	6.87	3.3	2.17

Table 3. Distribution of Average Irradiance Energy of Solar Energy (MJ/m^2) per Season in Taipei (Latitude 25.5°N, Longitude 121.5°E)

Time	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
Spring	0.20	0.50	0.85	1.17	1.62	1.44	1.34	1.14	0.89	0.72
Summer	0.45	0.94	1.56	1.82	1.96	2.07	2.00	1.83	1.38	0.97
Autumn	0.05	0.45	0.78	1.13	1.46	1.53	1.38	1.13	0.82	0.44
Winter	—	0.14	0.50	0.82	0.92	1.15	1.26	1.20	0.81	0.48

Table 4. Track of the Sun per Season in Taipei (Latitude 25.5°N, Longitude 121.5°E)

	Time (h)	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
Summer Solstice	Elevation Angle	24.1°	37.3°	50.7°	64.2°	77.8°	87.8°	74.7°	61.1°	47.6°	34.2°
	Azimuth Angle	74.1°	78.6°	82.9°	87.4°	94.4°	226.4°	267.8°	273.7°	278.1°	282.4°
Vernal Equinox	Elevation Angle	15.21°	28.51°	41.3°	53°	61.9°	64.9°	60.2°	50.4°	38.4°	25.46°
	Azimuth Angle	97.2°	104.6°	114.2°	128.2°	150.9°	184.1°	215.4°	235.6°	248.3°	257.3°
Winter Solstice	Elevation Angle	4.2°	15.6°	25.9°	34.3°	39.8°	41.4°	38.8°	32.6°	23.6°	13.1°
	Azimuth Angle	118.1°	125.8	135.7°	148.3°	164.1°	182.1°	199.8°	214.9°	226.8°	236.5°

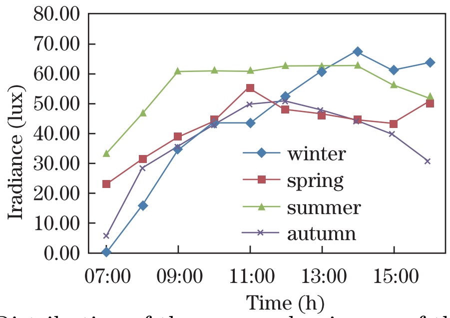

Fig. 10. Distribution of the average luminance of the sun per hour per season.

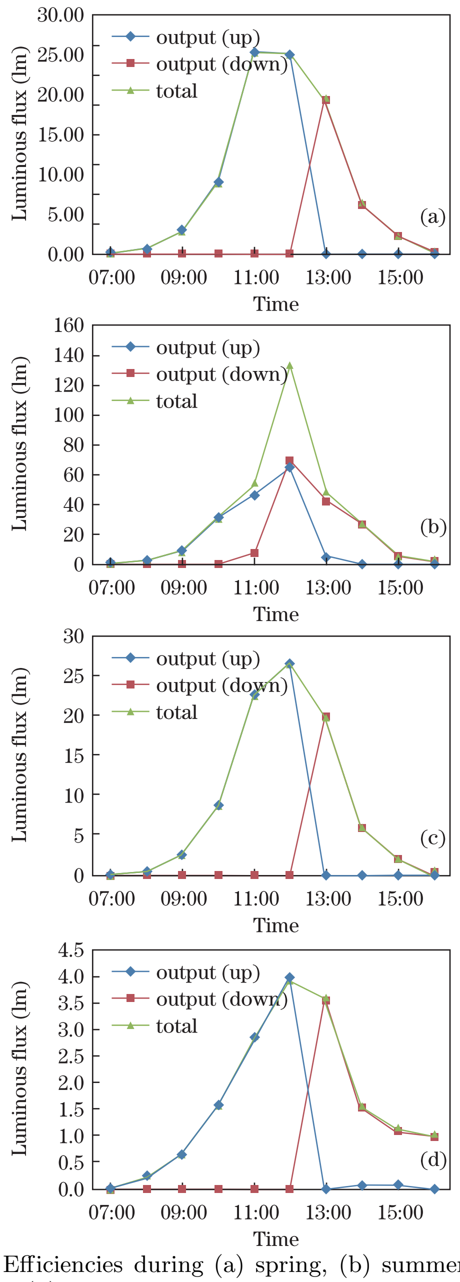

Fig. 11. Efficiencies during (a) spring, (b) summer, (c) autumn, and (d) winter.

Table 3 shows the sunlight data from the Central Weather Bureauin Taipei (latitude 25.5°N, longitude 121.5°E) and the distribution of the average irradiance energy from 7:00 AM to 6:00 PM for each season. The total irradiance energy in spring is 10.47 MJ/m^2, which is close to that in autumn (9.25 MJ/m^2). The total irradiance energy in summer (16.01 MJ/m^2) is clearly higher than those in other seasons. From the Central Weather Bureau, Table 4 lists the track of the sun during each season in Taipei. Figure 10 shows the distribution of the average luminance of the sun per hour per season.

Sunlight data in Taipei from the Central Weather Bureau are applied to our simulation to analyze actual situations. TracePro is used to perform ray tracing for different sun tracks in each season and to transform irradiance into luminous flux on the emitting surface for analysis. In Fig. 11, the unit of the vertical axes represents the luminous flux. Irradiance is the power of electromagnetic radiation per unit area (radiative flux) incident on the surface (lm/m^2). Figures 11(a)-(d) list the efficiency at different times (horizontal axes) during various seasons. Considering that sunlight forms a vertical angle to the ground at approximately 12:00 PM to 1:00 PM (Table 4), the output efficiency of the collector is highest during this period in each season. The average irradiance is highest during summer. Thus, the module output efficiency is also highest during this season.

In conclusion, we demonstrate a new module of a static concentrator that consists of a prism array. The maximum output efficiency of the concentrator module is 57%, and the maximum tolerance angle is 10°. The proposed module can be used widely in buildings to collect sunlight for indoor illumination and to provide healthy and clean illumination by decreasing carbon dioxide emission as much as possible. Our future research aims to increase the efficiency of this module and to keep the output energy stable throughout the day. In the future, indoor illumination will no longer need electrical power.

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