

Innovative coupler design based on a tapered light pipe with lens

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Received July 7, 2013; accepted October 17, 2013; posted online December 9, 2013

Natural light illumination system (NLIS) generates increasing research interest because of the recent trend toward green energy. Various crucial optical components used in a NLIS are analyzed, designed, and fabricated to obtain high efficiency. A large amount of light is loss because of the large viewing angle during light transmission. A tapered light pipe (TLP) is used to collimate light viewing angles. In this letter, we combine a TLP and a traditional lens as a new coupler based on Etendue theory. The original efficiency is only 17.54%, but the efficiency reaches more than 70% when the new coupler is applied.

OCIS codes: 220.4610, 220.4298, 220.3630.

doi: 10.3788/COL201311.122201.

The development of science and technology has led to a better living quality compared with that during previous periods. However, such improved quality is often accompanied by environmental pollution that causes numerous disasters, such as the decreasing number of animal species, climate change, and the greenhouse effect. Consequently, environmental protection has become increasingly important, and the development of green energy has become a trend worldwide. Any product related to “green” is currently popular. In architecture, green buildings have attracted numerous people, who have discovered that solar energy has an important role in our lives. A number of researchers have also been interested in developing solar cells^[1,2], but their efficiency is low because solar energy requires two energy transformations. Our team has developed a natural light illumination system (NLIS) that guides solar rays into interior areas. People who install this NLIS can enjoy sunlight inside their homes^[3,4]. The concept of NLIS includes three parts, namely, a light-collecting system (LCS), a light-transmitting system (LTS), and a light-emitting system (LES). For the LCS, we have developed the “light brick” module, which can guide light beams to the LTS through its prism structure. For the LTS, our team has developed the “light pipe”^[5] with a lens array inside it. The lens is designed according to the light distribution output of the light bricks, with a viewing angle of $\pm 10^\circ$. The light pipe can transmit beams at long distances and has the advantage of high efficiency and low price. Accordingly, the light pipe is considered as a feasible substitute to existing plastic optical fibers. For the LES, we have designed a light emitting tool to illuminate interior areas^[6] with high uniformity, low glare, and high illumination. The light brick can be placed on the roof of a building to connect light pipes via optical plastic fibers, and to transmit light beams to an interior area. We use plastic optical fibers between the LCS and the LTS to overcome

the problems of assembling the NLIS inside buildings because not all buildings are capable of having light pipes installed inside them. For the interface between the plastic fiber and the light pipe, we have not yet found a solution, and we simply connect the fibers directly to the light pipe. However, the viewing angle of the fiber is $\pm 60^\circ$, which does not satisfy the received requirements of the lens of the light pipe. In this study, we develop a new coupling approach to enhance the efficiency of NLIS. By using a tapered light pipe (TLP) with a lens design, we can effectively converge the viewing angle of the fiber to below $\pm 20^\circ$. Our new design can provide more than 70% output efficiency.

A NLIS includes three subsystems, namely, the LCS, the LTS, and the LES. We develop the LCS, i.e., the light brick, which can be placed on rooftops. The beams will pass through the LTS and the LES to the areas where illumination is required, as shown in Figs. 1 and 2.

In this study, we focus on the subsystems. The light brick is the primary concentrator^[7–10] that comprises certain 45° prisms that can change the light path effect-

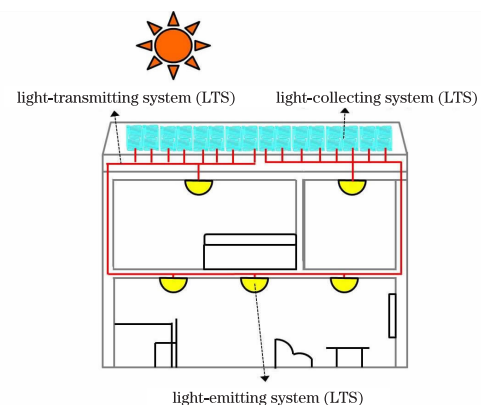


Fig. 1. Schematic of a NLIS.

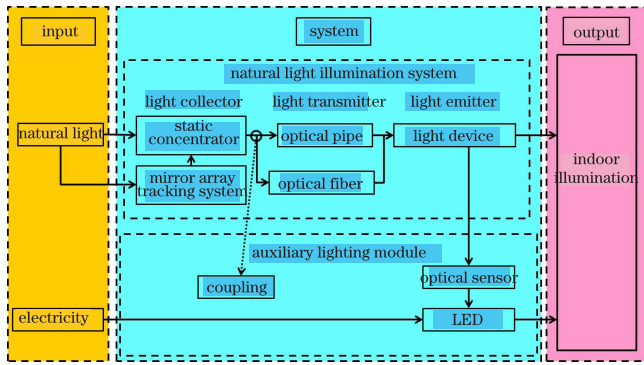


Fig. 2. Flowchart of a NLIS.

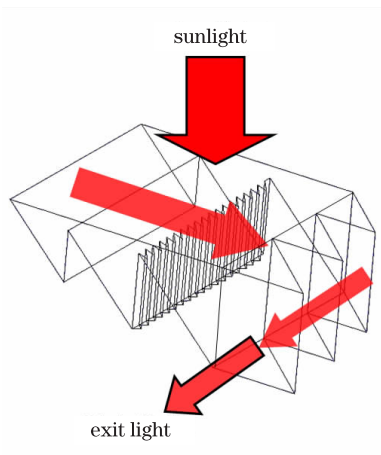


Fig. 3. Light brick unit.

ively. The light brick receives the parallel light beams, and then compresses the beams into a linear light source. Finally, the linear light source is transformed into a point light source at the output face, as shown in Fig. 3. We combine several light bricks into a light brick module.

We connect optical fibers with a 12-mm diameter at each exit face. In our design, we combine four light brick modules into a complete module, as shown in Fig. 4. Hence, we need eight 12-mm optical fibers for a complete light brick module.

To date, we have not yet developed a design for the interface between the fibers and the light pipe, that is, we directly connect the fibers to the light pipe. The light pipe has a lens design and can transmit light continuously.

With the optical fibers and the highly efficient light pipe, we can transmit light to an interior space more conveniently. We can also solve the building problems mentioned previously.

The light brick is a static solar concentrator. This concentrator does not require a sun tracker, and thus, it requires lower cost than a dynamic concentrator. The light brick consists of numerous prism structures that transform the light path from a collecting surface to a point light source output. We connect the light pipe through optical fibers. In this letter, we define the “power of the exit-surface of the light pipe divided by power of the exit-surface of the fibers” as the coupling efficiency. In the preliminary simulation, we analyze the energy loss caused by a large viewing angle input. The relation of intensity (radiant intensity: power per unit solid angle, W/sr) and

viewing angle from the exit surface of the fiber is $\pm 60^\circ$, as shown in the Fig. 5.

Based on our analysis, the coupling efficiency is approximately 17.54% without any coupling design. In this study, we combine a lens design to a TLP to reduce the viewing angle at the entrance of the light pipe.

We use two steps to collimate the viewing angles from the fibers. The first step uses a TLP. Several angle relations in a TLP are illustrated in Fig. 6 to describe the changes in viewing angle.

When the incident light beams arrive at the TLP interface, the incident light angle will be reduced to ψ° . Then,

$$\theta + y + 2x + \theta_2 = 180, \tag{1}$$

$$\theta_2 = 180 - (\theta + y + 2x), \tag{2}$$

$$\theta_2 = \theta_1 - 2\theta. \tag{3}$$

$$\psi = 2\theta, \tag{4}$$

$$\theta_2 = \theta_1 - \psi. \tag{5}$$

The incident light angle will reduce ψ each time it reflects from the TLP structure; thus, the viewing angle will become small. After several reflections, the viewing angle will be reduced to below 30° , depending on the length of the TLP. In this study, we increase the length



Fig. 4. Complete light brick module.

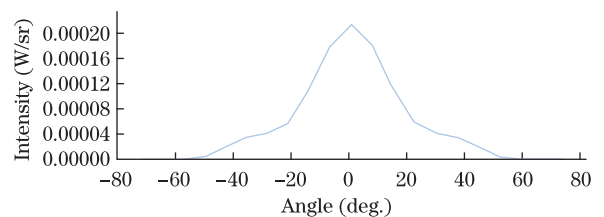


Fig. 5. Relation of intensity and viewing angle from the exit surface of the fiber.

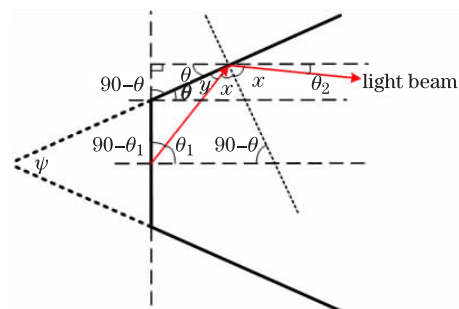


Fig. 6. Relations of a TLP angle.

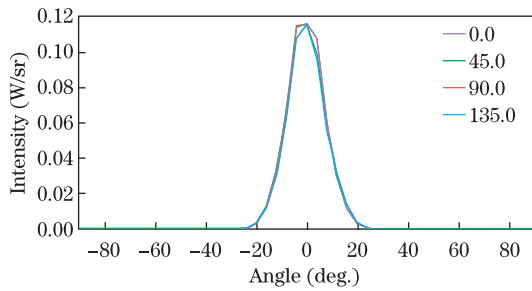


Fig. 7. Light distribution of the TLP design.

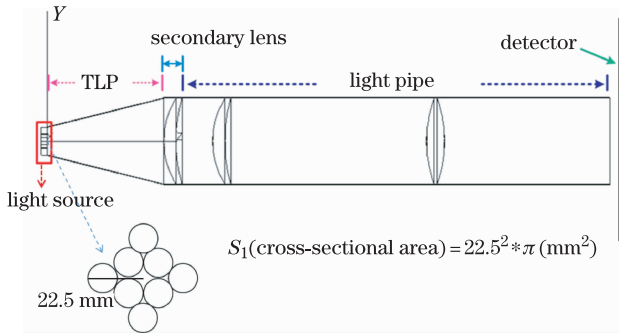


Fig. 8. Overall coupling structure.

of the TLP from 0.1 to 0.3 m. The experiment begins at 0.1 m, with an efficiency of 20.68%, which is close to the condition without design (with an efficiency of 17.54 %). In Fig. 7, the light distribution of the TLP is shown to be longer than 0.3 m.

In the second step, we combine our design with the light pipe. We install two lens to transmit the beams in the light pipe. This design can effectively reduce losses during transmission.

Our light pipe design includes two different lenses. The front and back curvature radiuses of the first lens are 130 and 250 mm respectively, with a thickness of 20 mm. The front and back curvature radiuses of the second lens are 200 and -200 mm, respectively, with a thickness of 30 mm. Our light pipe is designed for a light viewing angle between $\pm 10^\circ$, considering the viewing angle from the output surface of the light brick, which is approximately $\pm 10^\circ$. After the plastic optical fiber is bent to 90° , the viewing angle is extended to $\pm 60^\circ$. With the TLP, we can only collimate to above $\pm 20^\circ$. Thus, we add the first lens as an auxiliary lens^[11] between the TLP and the light pipe to shrink the viewing angle, as shown in Fig. 8.

We calculate the small angle limit via Etendue theory. The limit value of the viewing angle is 16.16° .

$$\text{input_area} * (\text{inputNA})^2 = \text{output_area} * (\text{outputNA})^2, \tag{6}$$

$$S_1 * n_1^2 \sin^2 \theta_1 = S_2 * n_2^2 \sin^2 \theta_2, \tag{7}$$

$$22.5^2 * \pi * l \sin^2 60 = 70^2 * \pi * \sin^2 \theta, \tag{8}$$

$$\theta = 16.16^\circ. \tag{9}$$

As shown in Fig. 9(a), the light distribution of a 10-m TLP is considered as a perfect condition. The light distribution of a 0.3-m TLP with an auxiliary lens is described

in Fig. 9(b). The viewing angles are 20° for 10-m TLP and 0.3-m TLP with an auxiliary lens. The energy is low at the reviewing angles. The obtained results agree with Etendue theory.

In this study, we add two structures as a coupler to collimate the light viewing angles. We assume that the energy of the exiting light from the fiber is 100%, and that the energy of the light passing through the fiber directly into the light pipe remains at 17.54%. We simulate three different conditions which are described as follows.

Under the TLP without lens condition, we choose an appropriate length for the TLP in our system from 0.1 to 0.3 m because the efficiency will not be higher than the condition without a coupler if the TLP is shorter than 0.1 m. The cost will also be high and hard to break even if the TLP is too long. The relation between efficiency and length is shown in Fig. 10 and Table 1.

Under the second condition, we use a TLP with an auxiliary lens as a coupler. The TLP length is the same as that in the first condition. However, we add one lens in light pipe as shown in Fig. 11 and Table 1.

The third condition is the one that we actually use in our system. Under the first and second conditions, we use a 100% reflection coating as the perfect TLP reflector. Under the third condition, a 95% reflection coating is used for the actual situation. The best TLP length is

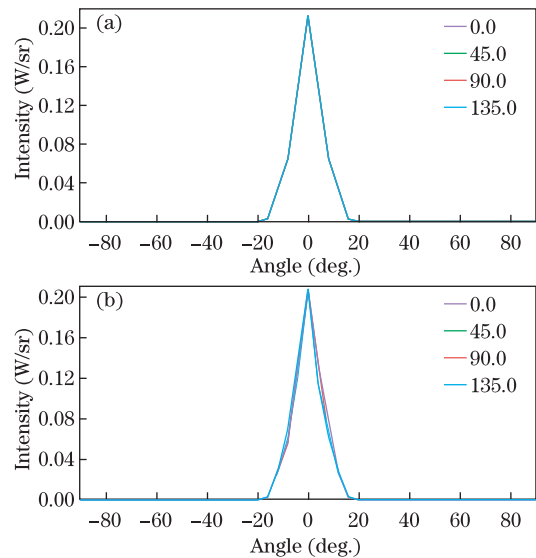


Fig. 9. Light distributions of (a) the 1000-cm TLP design and (b) the 30-cm TLP with an auxiliary lens design.

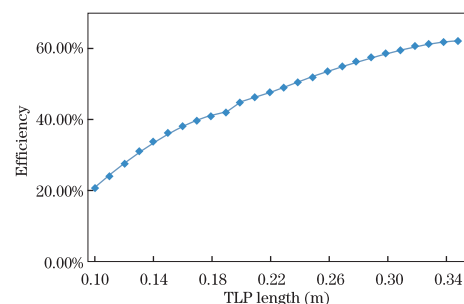


Fig. 10. Relation between efficiency and TLP length.

observed in this coupler. As a result of the 95% reflection coating, the best TLP length is 0.32 m, as shown in Fig. 12 and Table 2.

In conclusion, we design an innovative coupler based on a TLP with lens, which effectively enhances the trans-

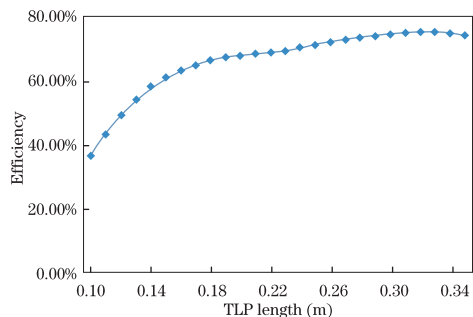


Fig. 11. The relation between efficiency and the length of the TLP with one lens.

Table 1. Output Efficiency Based on 100% Coating on the TLP Surface

Length (m)	Efficiency (with TLP)	Efficiency (with TLP and Lens)
0.1	20.68%	36.47%
0.15	36.24%	60.77%
0.2	44.84%	67.72%
0.25	52%	71.06%
0.3	58.61%	74.31%
0.31	59.42%	74.91%
0.32	60.55%	75.12%
0.33	61.23%	75.03%
0.34	61.89%	74.65%
0.35	62.04%	73.97%

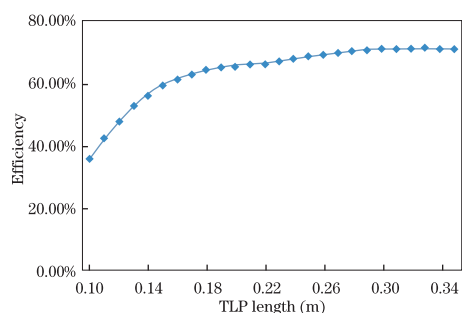


Fig. 12. Relation between efficiency and the length of the lens with TLP (with 95% reflection coating).

Table 2. Output Efficiency Based on 95% Coating on the TLP Surface

Length (m)	Efficiency (with TLP 95% Reflection Coating and Lens)
0.10	29.7%
0.15	59.6%
0.20	65.84%
0.25	68.53%
0.30	71.14%
0.31	71.43%
0.32	71.52%
0.33	71.49%
0.34	71.28%
0.35	70.99%

mission efficiency of a NLIS from 17.54% to more than 70%. We use a TLP reflector with a lens as the coupler. However, the coating method is expensive and difficult to maintain. We can use a free-form total internal reflection lens to design a coupler in the future. This process is an effective means to avoid coating and to realize a more efficient method for NLIS.

References

- 1 J. Fang, H. Zhang, H. Jia, H. Yin, S. Chang, and S. Qin, *Chin. Opt. Lett.* **8**, 478 (2010).
- 2 S. Zhang, Q. Wang, D. Zhu, R. Li, and C. Liu, *Chin. Opt. Lett.* **9**, 052201 (2011).
- 3 C. Chen, Y. Chen, A. J. Whang, and L. Chen, *Proc. SPIE* **7423**, 74230O (2009).
- 4 A. J. Whang, C. Lin, N. Ku, and M. Wang, *J. Renewable Sustainable Energy* **4**, 063118 (2012);
- 5 A. J. Whang, P. Li, Y. Chen, and S. Hsieh, *J. Display Technol.* **5**, 104 (2009).
- 6 A. J. Whang, Y. Chen, and Y. Teng, *J. Display Technol.* **5**, 94 (2009).
- 7 A. J. Whang, Y. Chen, and B. Wu, *Solar Energy* **83**, 1115 (2009).
- 8 A. J. Whang, C. Wang, and Y. Chen, *Renewable Energy* **34**, 2280 (2009).
- 9 C. Chen, Y. Chen, and A. J. Whang, *Proc. SPIE* **7422**, 74220Z (2009).
- 10 Y. Chen and A. J. Whang, *Proc. SPIE* **7428**, 74280E (2009).
- 11 S. Yang, Y. Chen, and A. J. Whang, *Proc. SPIE* **7423**, 74230J (2009).
- 12 Y. Bai, H. Zhang, J. Wang, N. Chen, J. Yao, T. Huang, X. Zhang, and Z. Yin, *Chin. Opt. Lett.* **9**, 032901 (2011).