*International Journal of Engineering Inventions*
*e-ISSN: 2278-7461, p-ISSN: 2319-6491*
*Volume 2, Issue 6 (April 2013) PP: 69-74*

# High-efficiency Light Couplers of Sunlight Guiding Systems for Indoor Illumination

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***Abstract:*** *We presented theoretical models of symmetric and asymmetric light couplers of daylighting systems for direct indoor illumination, and conducted numerical simulations using Matlab and Lighttools. Based on the simulation results, the accumulation coupling efficiencies are over 96% for the symmetric and asymmetric light couplers when large f-number concentrators (e.g., f/5.0) are used in a two-to-one light guiding system. When a large number of sunlight concentrators are used to gather sunlight and a coupling angle of 40 degree is assumed, the asymmetric couplers (58.6 %) provide higher coupling efficiencies of the guided sunlight than do the symmetric couplers (36.1%).*

***Keywords:*** *Coupling efficiency, day lighting Light coupler, sunlight guiding, solar energy.*

## I. INTRODUCTION

In the past 20 years, a large amount of greenhouse gases has been emitted into the earth's, atmosphere, resulting in global warming and dramatic climate change. In the third Conference of the Parties of the United Nations Climate Change Framework Convention, held in 1997, a target was set for the reduction of greenhouse gas emissions that countries must strive to achieve. One approach toward meeting this target is to reduce the consumption of fossil fuels by using solar energy [1]. Technologies that use solar energy include photovoltaic [2, 3], solar thermal [4, 5], and direct daylighting. The first two are categorized as the active technology and have been widely developed. However, few people in optical engineering have focused on direct daylighting, a passive technology, despite it offering advantages such as low cost, high efficiency for indoor lighting, and healthy illumination.

A daylighting system is constructed using sunlight collectors, a light guiding system, and light emitters [6-12]. Most sunlight collectors gather solar radiation by using optical convergent components such as a Fresnel lens and concave reflective mirror. Light emitters illuminate the interiors of large structures [8-11], such as tunnels, shopping malls, and underground parking lots by using planar diffusers or light rods. The function of the light guiding system is to transport and accumulate sunlight from the collectors and to the light emitters. To accomplish this, a light guiding system consists of trunk guides, branch guides, light couplers, and decouplers. A schematic of a daylighting system with a building layout is shown in Fig. 1, which contains four collectors on the roof, a system of light guides, and three light emitters in the house. The collectors are connected to the trunk guide through light couplers and the light emitters are connected through decouplers. For indoor lighting, many collectors are needed because only a limited amount of sunlight can be collected because of the finite area of each collector. In addition, when uniform illumination conditions are to be produced, many light emitters are needed. The result is a need for light couplers and decouplers with high efficiency in a daylighting system.

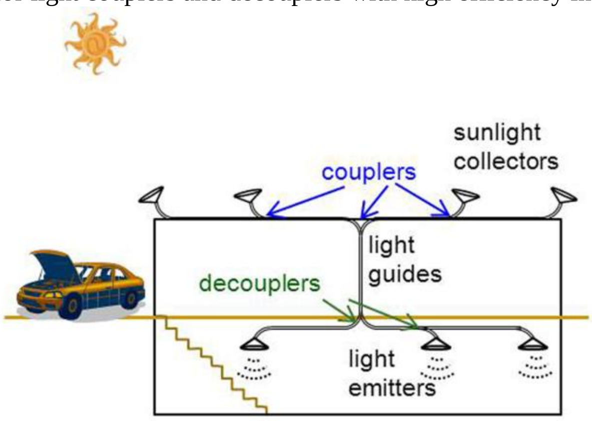



Fig. 1. Schematic of a daylighting system with a building layout.

Unlike the optical couplers in fiber communications that provide high coupling efficiency, the efficiency of the light couplers in daylighting systems is usually low because of the large core of the light guides. Efficiencies of 50% - 60% are typical [6, 11]; that is, almost half the amount of guided sunlight is lost in coupling. This study presents a method to increase the coupling efficiency. Based on the results, the asymmetrical light couplers can provide a higher coupling efficiency than the symmetrical couplers.

## II. METHODOLOGY

The coupling loss of light is derived mainly from the effect of total internal reflection (TIR). When a light ray travels through a coupler, the propagation angle of the light ray increases because of the reflection of the tilted interface of the coupler. When the propagation angle is larger than (90° - $\theta_c$), where $\theta_c$ is the critical angle, the ray leaves the light guide. Two coupling efficiencies are defined here. The angular coupling efficiency of the light rays with a certain propagation angle $\theta$ at the entrance of the coupler is defined as

$$\Delta\eta_\theta = \frac{\phi_{out}(\theta)}{\phi_{in}(\theta)} \tag{1}$$

where $\phi_{out}(\theta)$ and $\phi_{in}(\theta)$ are the light flux of the incident rays with propagation angle $\theta$ at the entrance and the exit of the coupler, respectively. The accumulated coupling efficiency $\eta_{\theta in}$ is defined as

$$\eta_{\theta_{in}} = \frac{1}{2\theta_{in}} \int_{-\theta_{in}}^{\theta_{in}} \Delta\eta_\theta d\theta \tag{2}$$

where $\theta_{in}$ is the maximum of the propagation angle at the entrance of the coupler.

A two-to-one light coupler with a symmetric structure, also called a symmetric Y-coupler, introduces the light rays from two entrances on one side and emits the rays at the exit on the other side, as shown in Fig. 2(a). The angle between the upper and the lower surfaces is the coupling angle $\theta_{coup}$. At each reflection by the two surfaces, the propagation angle increases by the coupling angle $\theta_{coup}$. When the propagation angle becomes larger than (90° - $\theta_c$), no more TIR occurs. The ray partially transmits to the outer region and finally disappears entirely.

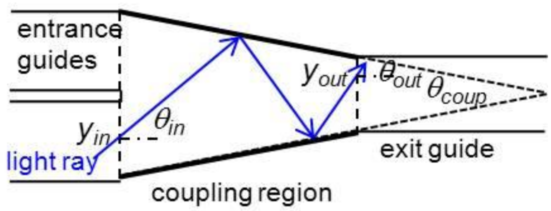
Suppose that an incident ray is characterized by the propagation angle $\theta_{in}$ and the coordinate $y_{in}$, defined as the distance from the lower surface. The propagation angle at the exit, $\theta_{out}$ is then obtained as

$$\theta_{out} = \left(1 - 4\left(m/2 - \lfloor m/2 \rfloor\right)\right) \times (\theta_{in} + 2m\theta_{coup}) \tag{3}$$

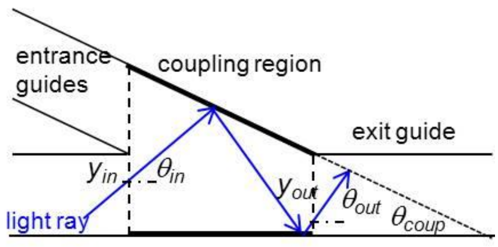
where $\lfloor x \rfloor$ denotes the largest integer less than or equal to $x$, and $m$ is the total number of reflections of a light ray traveling in the symmetric coupling region, given by

$$m = \lfloor \theta_{SCL} / \theta_{coup} \rfloor \tag{4}$$

Here, $\theta_{SCL}$ is the conjugate angle of the incident ray of $\theta_{in}$ at the exit, given by




(a) Symmetric coupler




(b) Asymmetric coupler

Fig. 2. Two-to-one (a) symmetric and (b) asymmetric light couplers for daylighting systems.

$$\theta_{SCL} = \left| \tan^{-1}\left(\frac{y_{PL}}{x_{PL} - W(1+\cos(\theta_{coup}))/\sin(\theta_{coup})}\right) \right| \tag{5}$$

where $W$ is the width of the light guide and, ($x_{PL}$, $y_{PL}$) are the coordinates of the intersection of the incident ray and the coupling circle, given by

$$(x_{PL}, y_{PL}) = \left( \frac{W + W_{gap}/2}{\tan(\theta_{coup}/2)} - \frac{W\cos\theta_{SCL}}{2\sin(\theta_{coup}/2)}, \frac{W\sin\theta_{SCL}}{2\sin(\theta_{coup}/2)} \right) \tag{6}$$

Here, $W_{gap}$ is the spacing of the two entrance light guides. The coordinate of the ray at the exit, $y_{out}$, is obtained as

$$y_{out} = \frac{W}{2}\left(1 - \frac{\theta_{in}}{|\theta_{in}|}\right) + \frac{\left| \frac{x_{PL}}{\tan(2m\theta_{coup})} - y_{PL} - \left(L_{coup} + \frac{W\tan(\theta_{coup})}{2}\right)/\tan(2m\theta_{coup}) \right|}{\sqrt{(1/\tan(2m\theta_{coup}))^2 + 1}} \times \frac{\theta_{in}}{|\theta_{in}|} \tag{7}$$

where $L_{coup}$ is the length of the coupling region, given by

$$L_{coup} = \frac{W}{2\cos\theta_{coup}} \tag{8}$$

In an asymmetric two-to-one light coupler, the exit guide is an extension of one entrance guide, called the trunk guide, and the other light guide, called the branch guide, enters at a tilted angle that is defined as the coupling angle $\theta_{coup}$. The geometry of the asymmetric Y-coupler is shown in Fig. 2(b). When a light ray travels through the coupling region, the propagation angle only increases at one of the surfaces. Therefore, light rays can travel longer distances. In addition, the coupling efficiencies of the two entrance guides are different, which provides flexibility in the design of light couplers.

Again, suppose that the propagation angle and the coordinate of an incident ray are $\theta_{in}$ and $y_{in}$, respectively. The propagation angle $\theta_{out}$ at the exit is obtained as

$$\theta_{out} = \left(1 - 4\left(m/2 - \lfloor m/2 \rfloor\right)\right) \times (\theta_{in} + 2\lfloor m/2 \rfloor \theta_{coup}) \tag{9}$$

where $m$ is the total number of reflections of a light ray traveling in the asymmetric coupling region, given by

$$m = 2 \times \left| \lfloor \theta_{ACL}/\theta_{coup} \rfloor / 2 \right| \tag{10}$$

Here, $\theta_{ACL}$ is the conjugate angle of the incident ray of $\theta_{in}$ at the exit, given by

$$\theta_{ACL} = \left| \tan^{-1}\left(\frac{y_{PL}}{x_{PL} - W(1+\cos(\theta_{coup}))/\sin(\theta_{coup})}\right) \right| \tag{11}$$

where ($x_{PL}$, $y_{PL}$) are the coordinates of the intersection of the incident ray and the coupling circle, given by

$$(x_{PL}, y_{PL}) = \left( \frac{2W}{\tan(\theta_{coup})} - \frac{W\cos\theta_{ACL}}{\sin(\theta_{coup})}, \frac{W\sin\theta_{ACL}}{\sin(\theta_{coup})} \right) \tag{12}$$

The output coordinate $y_{out}$ of the ray is obtained as

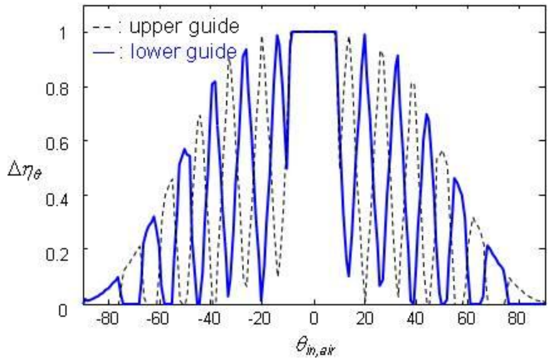
$$y_{out} = \frac{\left| x_{PL}/\tan(m\theta_{coup}) - y_{PL} - W(1+\cos(\theta_{coup})/\sin(\theta_{coup}))/\tan(m\theta_{coup}) \right|}{\sqrt{(1/\tan(m\theta_{coup}))^2 + 1}} \tag{13}$$

## III. SIMULATIONS AND DISCUSSION

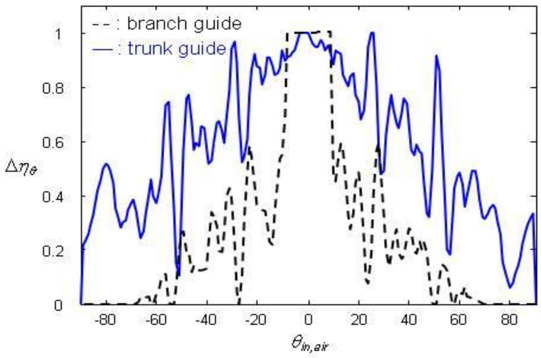
The simulations of light couplers were conducted using Matlab and Lighttools. The results of Lighttools were used to confirm the results of Matlab. The analysis of the simulation data, however, is based on Matlab results because the computation speed was considerably faster than using Lighttools. In simulations, the coupling angle was 40°, the dimension of the light guide was 4 mm, and the refractive index of the light guide was 1.460, resulting in $\theta_c$ = 43.23° (air outside). Note that the proposed method can be applied to the coupler of various coupling angle. The angle of light rays, $\theta_{in,air}$, incident from outside was ranged from -90° to 90°, and the corresponding propagation angle, $\theta_{in}$, of the light rays in the light guide ranged from -46.77° to +46.77°. We ignore the losses coming from the scattering and absorption of the guide material because the coupler is small in length of the coupler is small.

The angular coupling efficiency is the ratio of the output flux to the input flux of a specific angle of the incident rays. Because the losses of light rays result from the increase of the propagation angle after reflections, the efficiency profile is reciprocally symmetrical to $\theta_{in,air}$ = 0° for the two entrance guides of the symmetric coupler as shown in Fig. 3(a). The reciprocal symmetry of the efficiency profile is not significant for the guides of the asymmetric coupler, as shown in Fig. 3(b). The angular coupling efficiencies of the trunk guide was noted to be generally higher than those of the branch guide and the two guides of the symmetric coupler. When the input fluxes of the two light guides are assumed to be equal, the total angular coupling efficiency is the average of the angular coupling efficiencies of the inputs, which is shown in Fig. 3(c). The fluctuations in the efficiency profile of the asymmetric coupler result from the asymmetry of its structure.

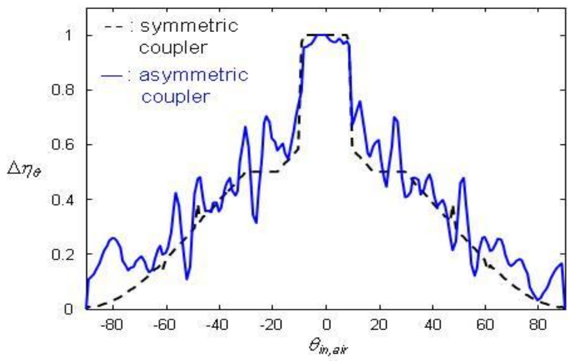
The sunlight within a solid cone is gathered, specified by the *f*-number, by a concentrating optical component. Therefore, the coupling efficiency of a light coupler should account for all the light in the possible propagation cone of the light guide or, for simplicity, average the angular coupling efficiencies in the cone, as shown in Eq. (2). The accumulated coupling efficiencies of the individual light guides, as shown in Figs. 3(a) and 3(b), are shown in Fig. 4(a). The accumulated coupling efficiencies of two input light guides of the couplers are shown in Fig. 4(b), calculated from Fig. 3(c). For full NA incident light, that is, $\theta_{in,air}$ = 90°, the $\eta_{\theta in,air}$ of the asymmetric coupler (41.5 %) is 6% higher than that of the symmetric coupler (35.7%). Both coupling efficiencies are inadequate for day lighting applications because more than 50% of the transported light is lost. However, this is not the case of interest.




(a) Symmetric coupler ($\theta_{coup}$ = 40°)




(b) Asymmetric coupler ($\theta_{coup}$ = 40°)



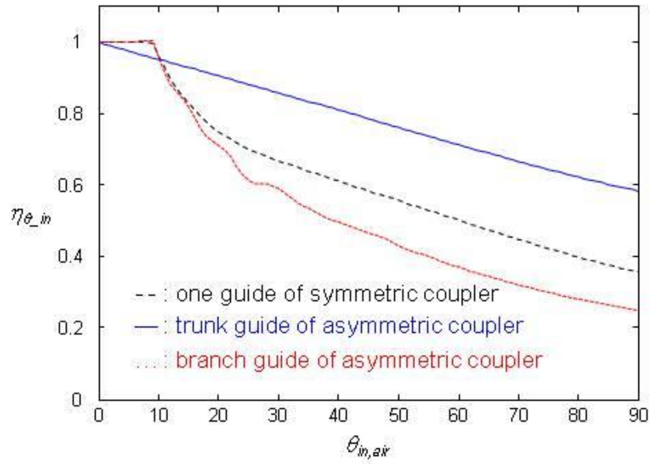

(c) Total angular coupling efficiency ($\theta_{coup}$ = 40°)

Fig. 3. Angular coupling efficiencies of (a) symmetric coupler, (b) asymmetric coupler, and (c) the comparisons, for 40° coupling angle.

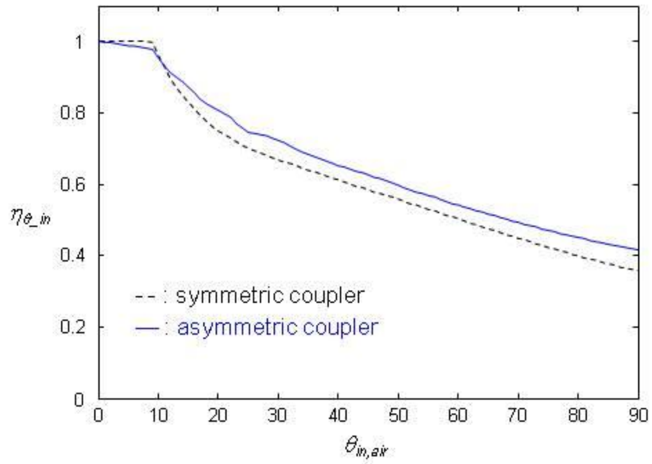
Most daylighting systems use concentrating collectors with a small *f*-number compared to the numerical aperture of the light guides. When *f*/0.5 concentrators are used, that is, $\theta_{in,air}$ = 45°, the $\eta_{\theta in,air}$ of the symmetric and asymmetric couplers are 58.4% and 62.5%, respectively, and, the $\eta_{\theta in,air}$ are 66.8% and 72.3%, respectively, when using *f*/0.87 concentrators ($\theta_{in,air}$ = 30°). The accumulated coupling efficiency can be up to 96% when *f*/5.0 concentrators ($\theta_{in,air}$ = 10°) are used in a daylighting system.

For the application of accumulating sunlight using multiple sunlight concentrators in a daylighting system, the propagation angle of the traveling light rays in the trunk guide ranges over ±(90° - $\theta_c$), corresponding to ±90° of $\theta_{in,air}$ because of the increase of the propagation angle after reflections at the tilted surfaces. The $\eta_{\theta in,air}$ of the trunk guides are 36.1% and 58.6% for the symmetric and asymmetric couplers with $\theta_{coup}$ = 40°. Supposing that *f*/1.0 concentrators ($\theta_{in,air}$ = 25°) are used, the $\eta_{\theta in,air}$ of the branch guides are 70.0% and 61.1%, which result into the total $\eta_{\theta in,air}$ of 53% and 60% of the $\theta_{coup}$ = 40° symmetric and asymmetric couplers, respectively.

As the amount of the accumulated light in the trunk guide greatly increases, the accumulated coupling efficiencies of the two couplers approach the (90° - $\theta_{in,air}$) values of the solid-blue and the dashed-black curves in Fig. 4(a), that is, 36.1% and 58.6% for the symmetric and asymmetric couplers, respectively. This shows the significance of using the asymmetric couplers in the sunlight guiding system.




(a) Accumulated coupling efficiency of individual light guides.




(b) Total accumulated coupling efficiency.

Fig. 4. Accumulated coupling efficiencies of the symmetric coupler and the asymmetric coupler with $\theta_{coup}$ = 40°. The total $\eta_{\theta in,air}$, as shown in (b), is calculated by assuming the fluxes of the input light guides are equal.

## IV. CONCLUSION

As great quantities of greenhouse gases have been emitted into the earth's atmosphere, resulting in global warming and dramatic climate change, the effective use of solar energy has become a critical issue. In recent years, many technologies of solar energy usage have been developed, such as photovoltaic, solar thermal, and direct daylighting. Daylighting systems, which collect and transport sunlight directly into building interiors for indoor illumination, can reduce the conversion losses between different forms of energy, and thus, increase the efficiency of using solar energy.

A daylighting system consists of sunlight collectors, a light guiding system, and light emitters. To collect a sufficiently large amount of sunlight for indoor illumination, a large number of sunlight collectors and high-efficiency light couplers are needed. Unlike the high-efficiency optical couplers used in fiber communications, the efficiency of the light couplers in light guiding systems is usually low because of the large core of the light guides. To increase the coupling efficiency of the light couplers, we developed theoretical models of the symmetric and asymmetric light couplers, and conducted numerical simulations of the light couplers with 40° coupling angle using Matlab and Lighttools. Based on the simulation results, the accumulation coupling efficiencies are over 96% for the symmetric and asymmetric light couplers when large *f*-number sunlight concentrators, for example, *f*/5.0, are used in a two-to-one guidance system. When a large number of sunlight concentrators are used to gather sunlight, the asymmetric couplers (58.6%) provide higher coupling efficiencies of the guided sunlight than do the symmetric couplers (36.1%).

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