

A brighter place: overview of microstructured sunlight guide

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ABSTRACT

Purpose: This article provides an overview of the daylighting system using existing and advanced submicron technology for buildings. The approaches of movable and fixed sunlight guiding system for saving the energy of artificial lighting will be reviewed. The major part is devoted to the sunlight guide panel / film based on a formed prismatic microstructure on transparent substrate by UV-imprint and roll-to-roll process.

Design/methodology/approach: To achieve the prismatic microstructure sunlight guide panel / film, the wide aspects including the suitable materials, optical design of the microstructure and tuning the imprint processes are covered. In addition, to estimate the effectiveness of sunlight guide panel / film, a series of experiments were performed and compared with the prediction.

Findings: The analysis reveals the outgoing light above the horizontal level of the transom in a major portion. It indeed provides the adequate indoor daylighting by the proposed sunlight guide panel / film.

Research limitations/implications: The use of micro-polygonal-structured sunlight guide panel/film to deliver the daylight into the core area of a building is recommended as future research to enhance the indoor illumination by daylighting system. The portion of outgoing light below 90° causes the glare.

Practical implications: The authors conclude the proposed prismatic sunlight guide panel/film is a promising approach for guiding daylight into a room.

Originality/value: The reviewed daylighting system with submicron-patterned prismatic sunlight guide panel/film made of inorganic-organic materials is based on the authors' original work of daylighting techniques. It significantly elevates the use of sunlight and saves energy consumption in a building.

Keywords: Sunlight guide; Imprint; Roll-to-roll; Hybrid material

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1. Introduction

1.1. Energy saving

Currently many countries devote to energy saving and carbon reduction. Sustainable development becomes the most important worldwide task. To achieve the goal, the 'Green Building' is one of the common means. Generally, the artificial light accounts for a great part of the total energy consumption of a standard office building. In an efficient office building, it can save about 80% of the energy consumed by artificial light by means of using high-efficient fluorescent lamps and lighting control, which switched off lamps when the lighting intensity exceeds the norm. The chart of energy consumption in an office building is shown in Fig. 1 [1]. It's well known that daylight is an essential resource providing plenty of energy and ubiquitously available; moreover, it will not drain away in the foreseeable future. Applying suitable daylighting systems to introduce natural light into the buildings for free has good potential for conserving energy.

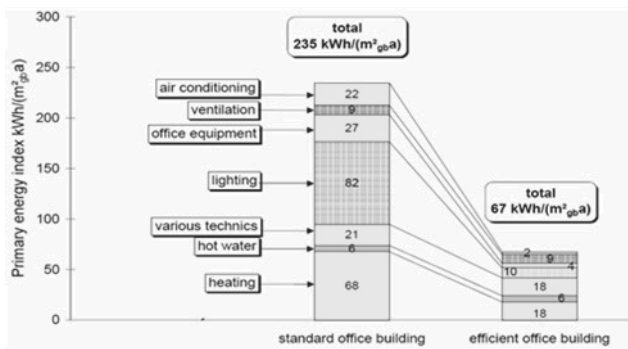


Fig. 1 Chart of energy consumption in an office building [1]

1.2. Daylight use

Daylight, in the main, is preferred above artificial lighting because it has perfect color rendering and a positive psychological effect on the human being. Hence, many architects attempt to provide daylight for a building wherever practical. Daylight consists of two components. The first is the direct sunlight beam that has high intensity and direction which varies with solar elevation angle. The second is the diffuse skylight scattering in the atmosphere.

Table 1. Typical values for some common lamp types compared with daylight [2-4]

Lamp	Electrical Input	Light Output	Luminous Efficacy
Incandescent Lamp	100 W	1360 lm	13.6 lm/W
Fluorescent Tube	58 W	5200 lm	90 lm/W
High-pressure Sodium Lamp	400 W	48 000 lm	120 lm/W
Sunlight (Solar Altitude: 7.5°)			90 lm/W
Sunlight (Solar Altitude: 25°)			117 lm/W
Skylight (Overcast - Clear)			110 - 175 lm/W

The luminous efficacy, the ratio of luminous flux (in lumens) to power (usually measured in watts), of daylight which includes direct sunlight, 90-117 lm/W, and diffuse skylight, 110-175 lm/W, is higher than artificial light, 13.6-120 lm/W. The daylight has the highest luminous efficacy even in an overcast day. The luminous efficacies of different light sources are shown in Table 1 [2-4]. According to the observation of International Commission on Illumination (CIE), the illuminance of cloudy sky, 5,000-20,000 lux, is lower but 10-50 times the indoor illuminance. Making provision for daylight to come into a room reduces the usage of artificial light. However, to provide good lighting there are three factors that should always be considered: the quantity, and quality of light, and its distribution. Intense sources of light (sunlight or electric light) can lead to severe glare which can be both irritating and debilitating. For this reason, controlling the admission of sunlight into a space requires the careful design of openings in a building [5].

2. Approaches to daylighting system

The components of the daylighting system are glazing and some other elements that enhances the delivery or control of natural light into a room. To improve the performance of daylight use, there are some solutions: providing usable daylight at greater depths from the window wall than is possible with conventional designs; increasing usable daylight for climates with predominantly overcast skies; increasing usable daylight for very sunny climates where control of direct sun is required; increasing usable daylight for windows that are blocked by exterior obstructions and therefore have a restricted view of the sky; transporting usable daylight to windowless spaces [5]. The daylighting system can be classified by two aspects, one is based on daylight condition, direct sunlight and diffuse skylight, that shown in Table 2 [5]; the other one is based on system mechanism, namely movable and fixed.

2.1. Movable Daylighting Systems

The movable daylighting system is divided into two mechanisms, manual control and automatic control, that can adjust the glazing to optimizing the quantity and quality of the incident natural light. The automatic daylighting system consists of a sensor, measuring incident flux, and a control system acting according to the sensor's signal which is capable of tracing the daylight and easier to design optical element, but increasing the system cost and consumption of electricity.

Solar Canopy Illumination System

Rosemann et al. [6] proposed a solar canopy illumination system which attaches to the building directly above the windows to alter the orientation of direct sunlight into the core area of a building. The sunlight is distributed within the building through a series of light guides which delivering the sunlight to the building and also efficiently incorporating electrical light sources so that they can provide supplemental lighting as necessary is shown in Fig. 2.

The tracking portion, as shown in Fig. 3, of the system is comprised of the “adaptive butterfly array”, an array of thin and roughly square mirrors, and protected from the weather by canopy, which enables the use of relatively cheap and lightweight materials. Each mirror in the array is supported by three fibers, the first and second which can be moved to position the mirror in any orientation in each of two corners of the mirror and the third in the center of the opposite edge, fixed. Fig. 4 shows the solar canopy was attached to the test facility.

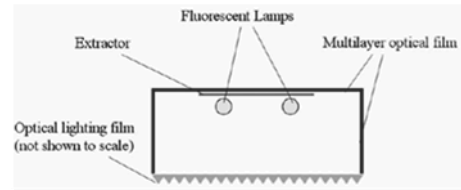


Fig. 2. Schematic drawing of the light guide [6]

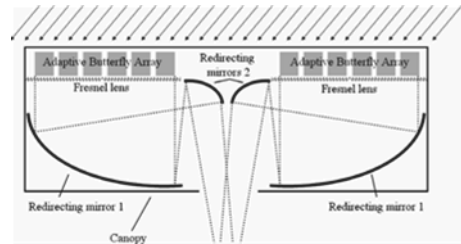


Fig. 3. Top view of the solar canopy system showing the concentrating and redirecting optics [6]

Micro Mirror Array System

Viereck et al. [7] demonstrated an electrostatically actuated micro mirror arrays, millions of micro mirrors, between the panes of a double glazing window. Fig. 5 shows the basic functionality of system. Each window is divided into two parts and using an intelligent sensor system, therefore, any required illumination configuration can be obtained. This diversity is not possible with standard blinds. Due to the small size of the micro mirrors, the vision through the mirrors in the open-position is nearly undisturbed.

In other mirror positions, the window appears like a more or less tinted window which the outside vision is maintained. Furthermore, implementation between the two panes protects the mirrors against wind, weather and defilement that present high mechanical stability and long lifetime of microstructures, and the system is expected to be maintenance-free for many years. The drawing and SEM-micrograph of micro mirrors is shown in Fig. 6.



Fig. 4. Test facility with solar canopy [6]

Table 2. Daylighting systems of different daylight conditions [5]

Natural Light Type		Direct Sunlight			Diffuse skylight
System Type	Mirror Louver or Blind	Light Guiding Shelf/ Light Shelf for Redirection	Laser Cut Panel/ Prismatic Panel	Sun-directing Glass	Light Shelf
Sketch					
Criteria for the Choice of Elements	Glare Protection	Y	Y	N	D
	View Outside	Y	D	Y	N
	Light Guiding into Depth of Room	D	Y	Y	Y
	Saving Potential	D	Y	Y	Y
	Need for Tracking	N	Y	N	N

Y= Yes, D= Depends, N= No

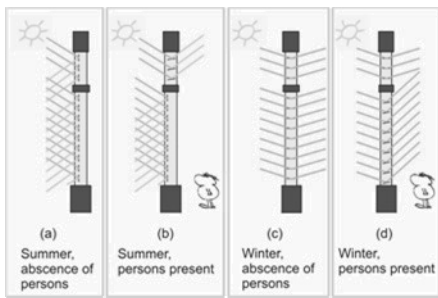


Fig. 5. Schematic cross section of a window within housed micro mirror arrays in different situations [7]

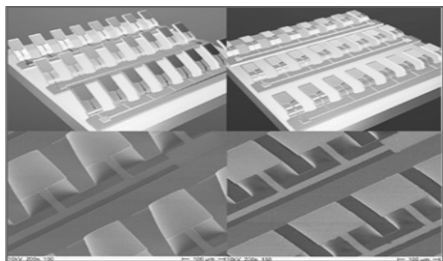


Fig. 6. Drawing and SEM-micrograph of micro mirrors in half opened position (left) and closed position (right) [7]

ASZEN System

Kinney et al. [8] indicated the ASZEN system (Fig. 7) which intercepts beam sunshine by horizontal and vertical reflective elements. A single microcontroller controls sets of front end ASZEN light-redirecting systems in a coordinated manner to achieve uniform and glare-free natural lighting environment by directing sunlight across a ceiling and onto the tops of the far sidewall is shown in Fig. 8.



Fig. 7. ASZEN front end illustration [8]

2.2. Fixed daylighting systems

The fixed daylighting system redirects the daylight by designing the optical structure of the glazing. The optical design of the fixed daylighting system which suitable for all daylighting condition is more difficult because daylight varies constantly in intensity, color and luminance distribution by solar elevation angle; but, it lessens the cost of system and electricity.

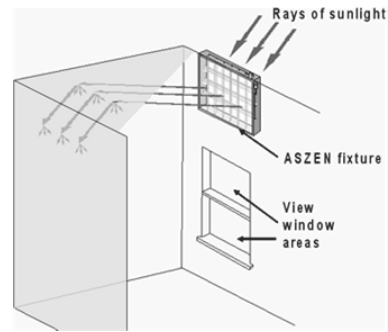


Fig. 8. ASZEN system as ceiling washer [8]

Laser-cut Panel

Edmonds et al. [9] brought out a laser cut panel which is a daylight deflection system, Fig. 9(a), produced by making narrow parallel laser cuts in a sheet of clear acrylic. Each cut surface deflects the daylight by refraction and total internal reflection is shown in Fig. 9(b). The orientation and deflective fraction, f , are determined by incidence angle, i , practical ratio of height to width, W/D , of rectangle ribs, and oblique angle of the panel. An advantage of the panel is that between the cuts, a outside vision of the window is maintained, but it is slightly distorted.

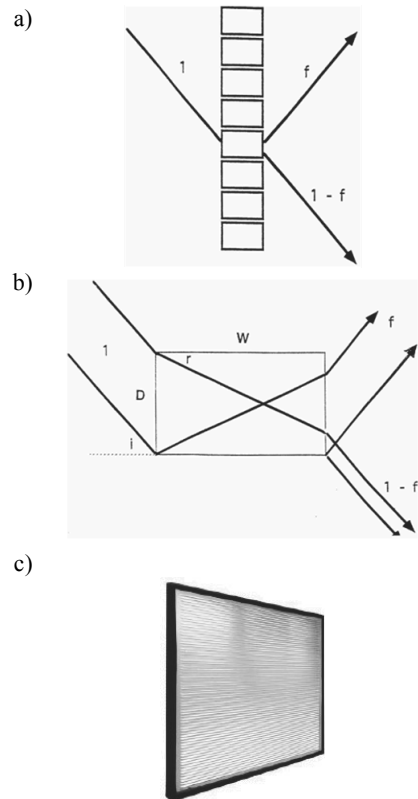


Fig. 9 Schematic laser-cut panel (a) cross section, (b) the deflection of daylight [9] and (c) picture [10]

Sun-directing Glass

The sun-directing glass is a double-glazing sealed vertically stack of opaque concave acrylic elements which redirect the direct sunlight from all incident angles toward the room ceiling. To avoid the obstruction of outside vision, the glazing is normally mounted above the view window. The sinusoidal surface of the acrylic elements could spread the outgoing light within a narrow horizontal, azimuthal angle, as shown in Fig. 10. These elements are well suited for installation between the double-pane window which protects the elements from contamination and weather. [5] Fig. 11 shows the picture of sun-directing glass.

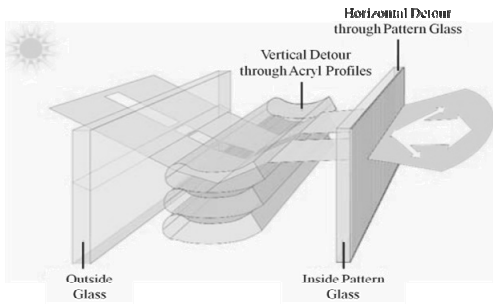


Fig. 10. Work principle schema of sun-directing glass [11]

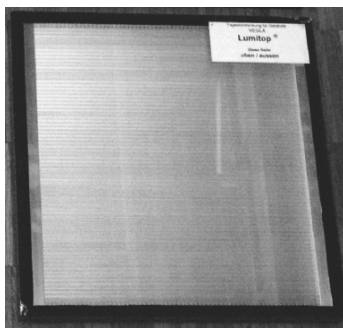


Fig. 11. Picture of sun-directing glass [10]

3. Prismatic Sunlight Guide Panel/Film system

Prismatic daylighting system is used to redirect or retract daylight, and usually made of clear acrylic that is used in temperate climates. There are many applications of prismatic system, in fixed or sun-tracking arrangements. Its design may redirect a part of the direct sunlight downwards, causing glare. However with a correct profile and seasonal tilting, these downward beams can be avoided [5]. The authors designed the prismatic sunlight guide panel / film capable for guiding sunlight into building room which are a formed microstructure on transparent substrate by UV-microimprint and roll-to-roll process will be introduced hereafter, respectively. Since the sunlight guide panel/film would disturb the outward vision due to the microstructures on the substrate, it is assembled on the transom of the building.

3.1. Inorganic-organic materials

Sunlight guide elements are commonly made of glass, thermoplastic polymer, or UV curing resin. However, it is difficult to imprint the microstructure onto a glass, and the weather resistance of the thermoplastic polymer and the UV curing resin are poor [12-14]. The inorganic-organic material is of interest. The inorganic-organic materials with high transmittance in the visible region, inorganics with positive properties (weather resistance and wear resistance), and organics (flexibility) are advantageous for fabricating micro optical devices [15-18]. A comparison of sunlight guide panel materials is listed in Table 3.

3.2. Optical design and analysis

Two types of polygonal prism to alter the direction of direct sunlight toward the room ceiling will be introduced to increase the brightness in the core of the building. The first type is the quadrangle, the second type is the combination of inclined and curved surfaces. The parameters of type 1 includes top feature at 45° and pitch of 50 μm is shown in Fig. 12(a). The features of type 2 includes inclined and curved surfaces with 18 μm-pitch and 21 μm-height. When sunlight beams shed on the prism surface, they refract at the interface between air and prism; then, the sunlight within the microstructure will be internal-reflected by the prism slopes. Finally, the sunlight through the microstructure at the right side surface, as shown in Fig. 12(a), is refracted toward the ceiling that becomes the outgoing light. There are three conditions of optical path of sunlight as shown in Fig. 12(b-d). The optical path can be calculated by refraction equation, Snell's law ($n_1 \sin \theta_1 = n_2 \sin \theta_2$), and reflection equation ($\theta_i = \theta_r$). For instance, the outgoing angle (θ_5) of optical path condition in Fig. 12 (b) is calculated as following:

$$\theta_1 = D - h \quad (1)$$

$$\theta_2 = \sin^{-1} \left(\frac{n_1}{n_2} \sin \theta_1 \right) \quad (2)$$

$$\theta_3 = 180^\circ + \theta_2 - (A + D) \quad (3)$$

$$\theta_4 = A - \theta_3 \quad (4)$$

$$\theta_5 = \sin^{-1} \left(\frac{n_2}{n_1} \sin \theta_4 \right) \quad (5)$$

An optical software TracePro® was used to simulate the outgoing angles of different elevation angle sunlight through the polygonal prisms in this study. The light source was assumed to be composed of parallel rays (see Fig. 13) because the sun is a far-flung star. The effective outgoing angle fell into the range of 90°-180°, from horizontal level of transom to room ceiling; thus, sunlight was redirected to the indoor ceiling by the polygonal prisms.

Table 3.
Comparison of sunlight guide panel materials

Material	PMMA	Glass	Inorganic-Organic Hybrid Material
Method of Patterning	Injection Molding	Hot-Embossing	UV Imprinting
Processing Temperature	200 °C	600 °C	150 °C
Hardness	4H	>7H	>6H
Weather Resistance	Worse	Good	Good
Weight	Light	Heavy	Moderate
Microstructure Fabricability	Good	Worse	Good
Fabrication Cost	Low	High	Low
Material Cost	Low	Low	High
Large Area Production	Moderate	Difficult	Easy

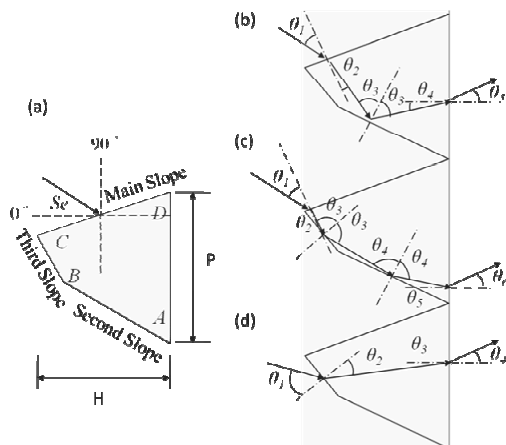


Fig. 12. (a) Parameters and (b-d) optical paths of quadrangle prism

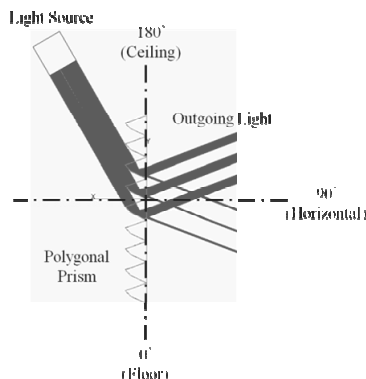


Fig. 13. Simulation of sunlight through the polygonal prism

3.3. Fabrication process

Sunlight Guide Panel by UV-imprint

The procedure for fabricating the sunlight guide panel of type 1 is shown in Fig. 14. A master mold was machined by the diamond cutting of an electroless nickel layer at a cutting speed of

10 m/min. The reverse type 1 microstructure was then transferred to polydimethylsiloxane (PDMS) in a vacuum oven from the master mold baked at 100 °C for 45 minutes. Afterward, the PDMS mold imprinted the microstructure onto the inorganic-organic hybrid material, which was coated on the glass under a pressure of 4kPa with a UV dose of 250mJ/cm². Fig. 15 shows the pattern images of the PDMS mold and the sunlight guide panel, by using scanning electron microscopy (SEM; Philips, Quanta 400F). The structures were transferred successfully. The fabricated sunlight guide panel is shown in Fig. 16 [19].

Sunlight Guide Film by Roll-to-roll

To improve the productivity and throughput, the roll-to-roll technology was used to fabricate flexible optical element extensively [20-23]. Fig. 17 shows the procedure for fabricating the sunlight guide film of type 2 by this method. The roll mold was fabricated by diamond turning lathe, and used for UV cured embossing process. In the embossing, the UV-curable resin was coated on transparent polyethylene terephthalate (PET) film first, then the PET film was transferred by the parameters of 3kg of tension and 3m/min of speed.

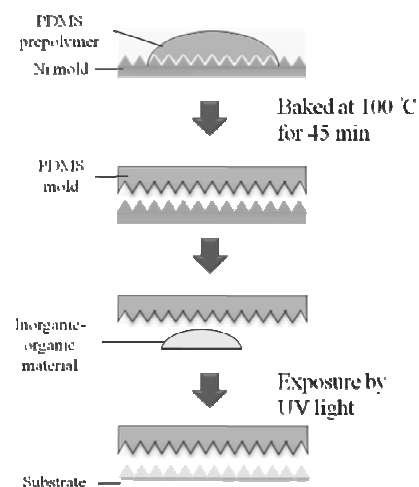


Fig. 14 Procedure for fabrication of the sunlight guide panel by UV-imprint [19]

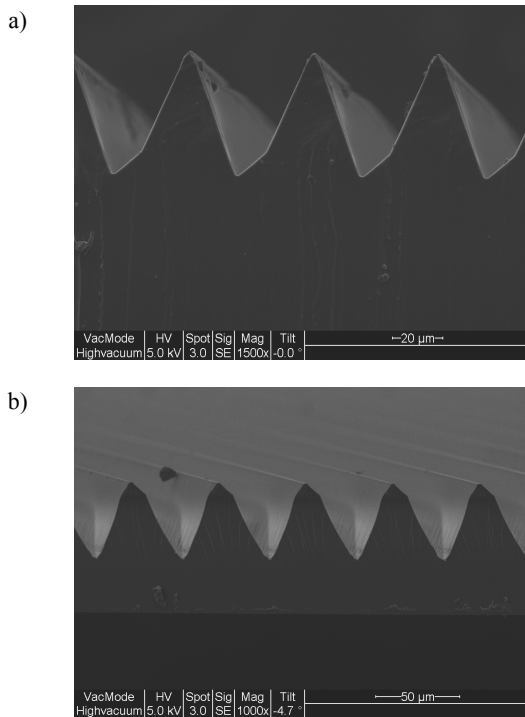


Fig. 15. SEM images of type 1 microstructure: (a) reverse microstructure of PDMS mold, (b) sunlight guide panel [19]

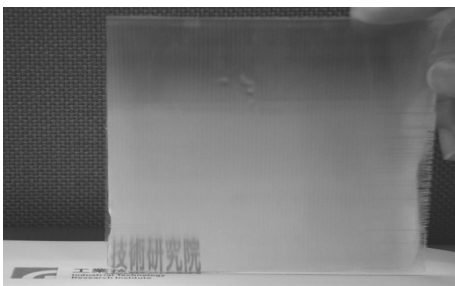


Fig. 16. Picture of the sunlight guide panel [19]

Finally, the resin was embossed by roll mold and cured by UV light, and the power of light was 120 W/cm^2 . Fig. 18 shows the SEM image of type 2 microstructure. A roll of sunlight guide film is shown in Fig. 19 [24].

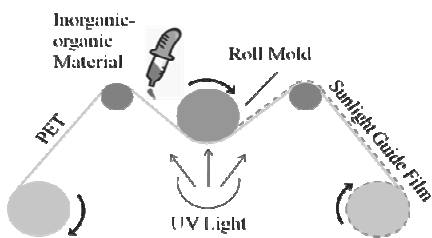


Fig. 17. Procedure for fabrication of the sunlight guide film by roll-to-roll process [24]

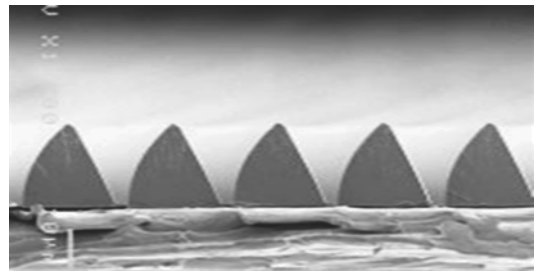


Fig. 18. SEM images of type 2 microstructure [24]

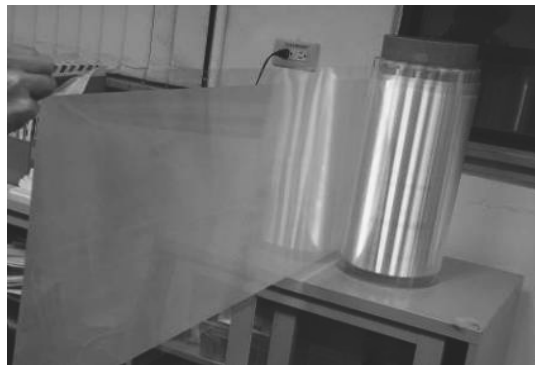


Fig. 19. Photograph of a roll of sunlight guide film [24]

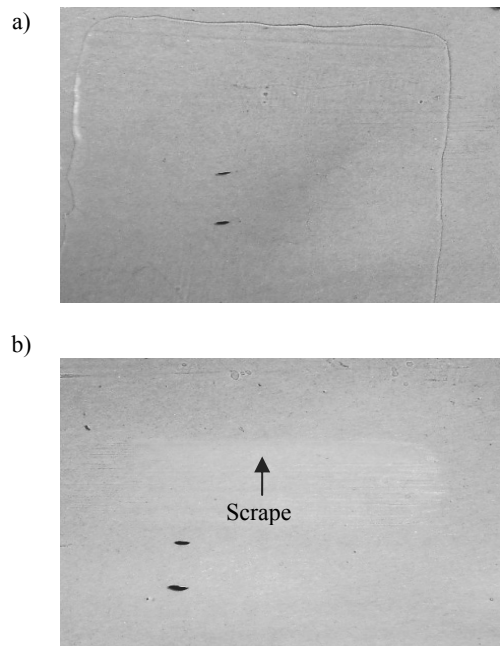


Fig. 20. Results of the wear test: (a) the inorganic-organic material and (b) the other UV-cured resin

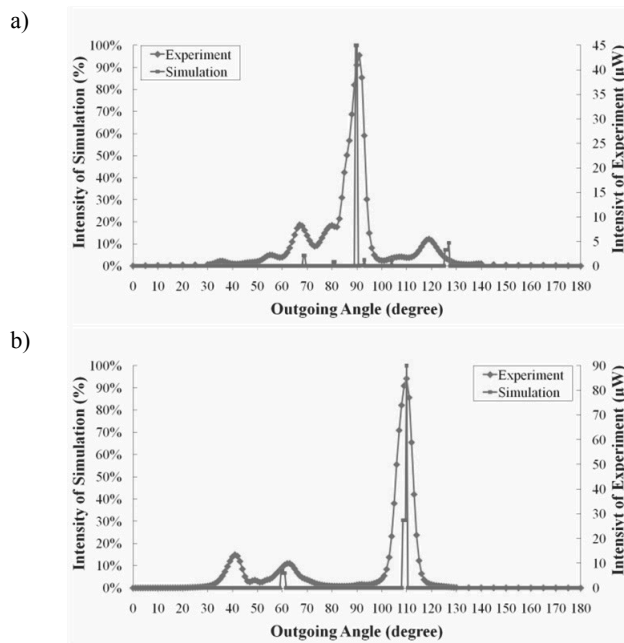


Fig. 21. Comparison of the experimental and the simulation results of type 1 panel at solar elevation of: (a) 40° and (b) 60° [19]

3.4. Measurement and verification

Wear Test

For outdoor applications, the wear resistance can be assessed with a test that follows the standards of the American Society for Testing Material (ASTM) D1044. The inorganic-organic material and other UV-cured resin were coated onto the polyethylene terephthalate (PET) film. A steel wool was rubbed 10 times on the surface of the material under 500g of load with a surface hardness abrasion tester (Comtech, QC-621D). The test results in Fig. 20(a) show that the inorganic-organic material had no scratches, whereas other UV-cured resin did (see Fig. 20(b)). Thus, the inorganic-organic material possesses a superior wear resistance than other UV-cured resin.

Optical Test

The optical performance of the sunlight guide panel with type 1 microstructure and film with type 2 microstructure were measured by the equipment that included a light source, photo detector, and rotators [24]. The experiments measured the outgoing light intensity at different solar elevation angles. The outgoing intensity at each angle was divided by the maximum outgoing intensity at different solar elevation angles. Fig. 21 shows a comparison of the outgoing light between the experimental and the simulation results of type 1 panel [19], and Fig. 22 is the comparison of type 2 film [24]. The outgoing angle of light with the maximum intensity at different solar elevation angles was above 90°.

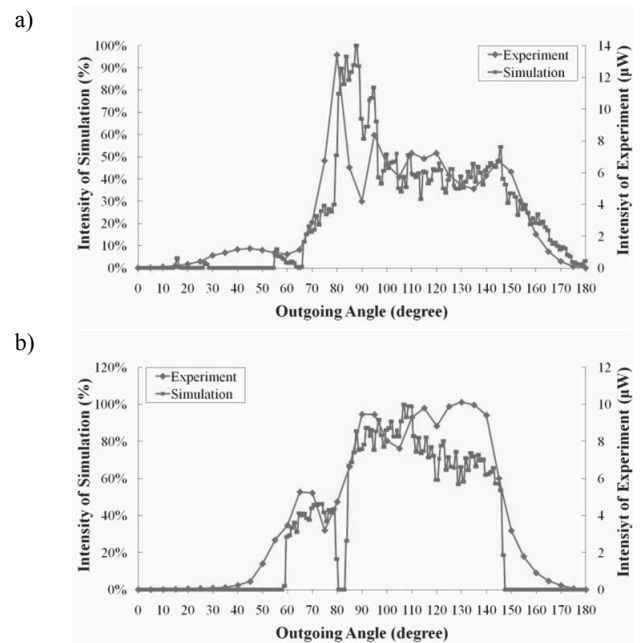


Fig. 22. Comparison of the experimental and the simulation results of type 2 film at solar elevation of: (a) 40° and (b) 60° [24]

The results show that adequate indoor lighting by sunlight can be provided by these sunlight guide panel/film.

4. Conclusions

The shortage of petrochemical energy and the increased greenhouse effect have caused serious concerns. How to extend the energy supplies by energy conservation and deal with the greenhouse effect by carbon reduction are important worldwide tasks. The artificial light consumes the greater part energy of an office building. Applying suitable daylighting system to introduce the natural and plenty of free-charge light is good alternative for conserving energy consumed by the artificial light.

The daylighting system can be classified by movable and fixed mechanisms. The movable system is capable of tracking the daylight and easier to design the optical parts, but increasing the cost due to extra sensor, control system, etc., and the consumption of electricity. The movable system can avoid the glare condition. The fixed system redirects the daylight by refraction and reflection of the designed optical units. The optical design for all daylighting conditions of the fixed system is more difficult because the daylight varies all the daytime with the solar elevation angle. Nevertheless, it lowers the cost, electricity and is easier to use than the movable one.

The micro-prismatic structures fabricated by UV-imprint and roll-to-roll process are introduced in this study. It can further reduce the cost of daylighting package due to its miniaturization. The roll-to-roll process improves the productivity and promotes the commercialization. To sustain the sunlight guide panel/film in the outdoor application, the inorganic-organic materials with good weather resistance, wear resistance and flexibility were used.

The optical measurement of these microstructures shows the outgoing light was mainly above 90° at different solar elevation angles. It shows that sufficient indoor lighting by redirected sunlight can be provided by the discussed sunlight guide panel/film. A significant energy saving can be achieved.

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