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Design and fabrication of sunlight-redirecting and infrared-insulating microstructure

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ABSTRACT

Air-conditioning and artificial lighting consume over 50% of the energy in a building. Decreasing thermal loading and introducing sunlight into a building can effectively save electricity and reduce greenhouse effect. This study reports a design for a passive prismatic sunlight-redirecting microstructure coupled with infrared (IR) insulation. The infrared insulation is an anti-reflection nanostructure with a silver thin film. The base design uses a quadrangular prism with a 45° vertex angle and a height and pitch of 50 μm to direct the high intensity sunlight deep into the room; unfortunately, this design produces harmful glare, and the area lighted by the redirected sunlight drifts as the varies sunlight during the day. The prism is further modified using an inclined-curved complex, which has 18.3 μm pitch and 20.91 μm height. The curved plane can diffuse the sunlight into a wide-angle exiting sunlight beam, which provides uniform sunlight with a stable daylighting area. The experimental results show that the daylighting redirection efficiency reaches 70% at solar elevation angles of 40–70° and that the daylighting area can reach up to 7 m deep into the room. The average transmittance is lower than 15.46%, and the reflectance is higher than 75.64% at infrared wavelengths.

1. Introduction

The impact of the greenhouse effect has been a serious concern. Many countries devote significant effort to developing energy-saving technologies and strategies for reducing carbon emissions for sustainable development. To achieve this goal, the 'Green Building' is an important approach. Fig. 1 [1] shows there are two major components that are responsible for over 50% of the energy consumption in a building in Taiwan: air-conditioning and artificial lighting. In the thermal loading of an air conditioner of office building in Taiwan, 20% is produced by lighting and 18% is produced by solar radiation (glass radiation and glass conduction), as shown in Fig. 2 [2]. Using a suitable daylighting system can save approximately 10–20% of the energy used for artificial lighting in a building. The daylighting system can be classified into tracking [3–5] and passive [6–10] types based on the system mechanism. This study decreases the thermal loading by using infrared (IR) insulation and introduces the powerful and free sunlight beam into and toward the room ceilings of the building via a passive sunlight-redirecting (SR) microstructure. This process can effectively lower the electricity consumption, as shown in Fig. 3. The proposed microstructure, fabricated by roll-to-roll embossing, demonstrates great potential for simultaneously reducing the energy consumption loading in air-conditioning and artificial lighting systems.

2. Optical designs and analysis

This study demonstrates the efficacy of a fixed prismatic SR microstructure coupled with IR insulation. The SR microstructure is capable of directing sunlight into the building's deeper rooms and was designed using ray tracing software, TracePro®. The IR insulation is formed by a sub-wavelength anti-reflection nanostructure and a silver thin film, which is capable of blocking the infrared portion of the sunlight spectrum and decreases the thermal load on the building. This study also simulates the IR blocking effects of different thicknesses of silver film using finite-difference time-domain (FDTD) software. Because the SR microstructure would disturb the outward vision from the room due to the microstructures on the substrate, it is assembled on the transom of the building, as shown in Fig. 3.

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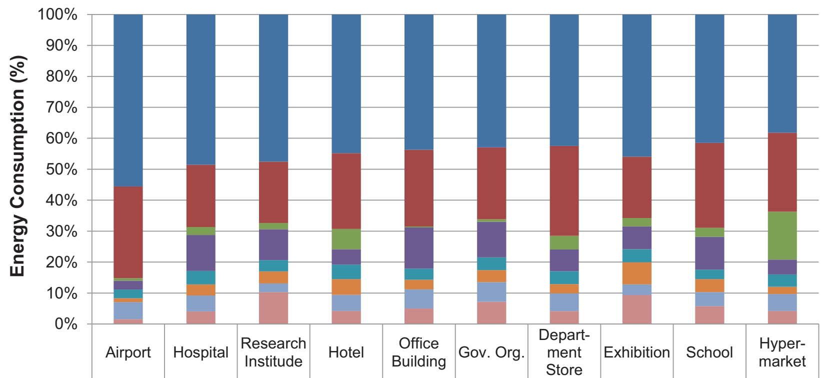

	Airport	Hospital	Research Institude	Hotel	Office Building	Gov. Org.	Depart-ment Store	Exhibition	School	Hyper-market
Air Conditioner	55.5	48.6	47.5	44.8	43.7	42.9	42.5	46	41.5	38.2
Lighting	29.6	20.1	19.8	24.5	24.8	23.2	29.1	19.8	27.4	25.5
Refrigerator	0.8	2.6	2	6.5	0.3	0.8	4.4	2.7	2.9	15.5
Socket	2.9	11.6	10	5	13.3	11.5	7	7.4	10.6	4.8
Ventilation System	2.8	4.4	3.6	4.7	3.6	4.1	4.2	4.2	3.1	4
Wastewater Treatment System	1.2	3.6	3.9	5.1	3.1	3.9	3	7.2	4.2	2.3
Escalator	5.5	5.1	2.8	5.2	6.2	6.3	5.7	3.4	4.5	5.5
Other	1.6	4.1	10.3	4.2	5	7.2	4.2	9.4	5.8	4.2

Fig. 1. Typical energy consumption values of various buildings [1].

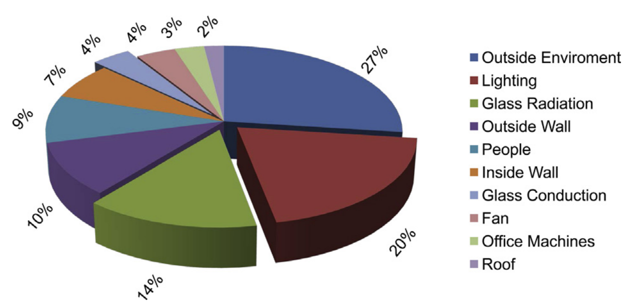

Fig. 2. Thermal loading of an air conditioner of office building in Taiwan [2].

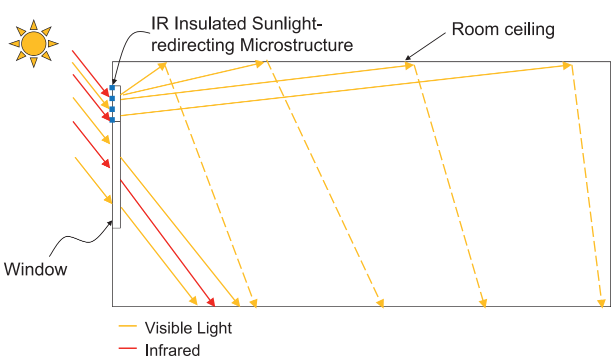

Fig. 3. Schematic of the work principle of IR insulated SR microstructure.

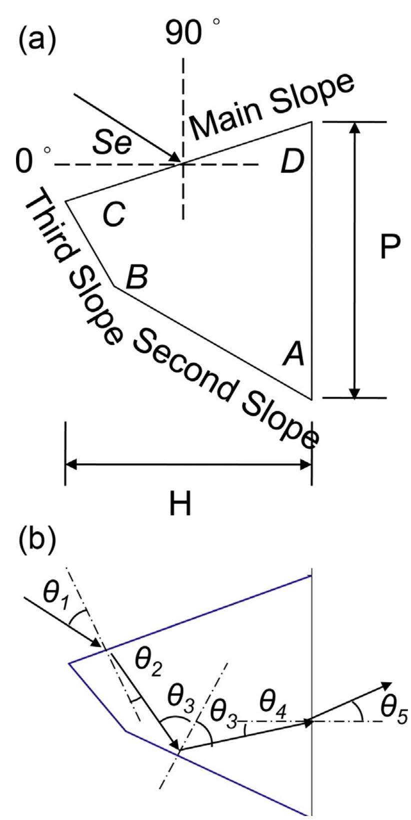

Fig. 4. Type 1 quadrangle prism (a) parameters and (b) representative optical path [11].

2.1. Sunlight-redirecting microstructure

2.1.1. Design principle

Two types of polygonal prism have been designed, which can direct the sunlight toward the room ceiling and increase the brightness in the core of the building. The first type is the quadrangle prism, which includes a top feature at 45° and a pitch height of 50 μm, as shown in Fig. 4(a). The sunlight is refracted at the interface between the prism and air, where it impinges on the prism surface. It is then internally reflected by the prism inclines within the microstructure. Finally, the sunlight ray exiting the microstructure from the right side plane, as shown in Fig. 4(b), is refracted toward the room ceiling and becomes the outgoing useful light. Using Snell's law ($n_1 \mathrm{Sin}\theta_1 = n_2 \mathrm{Sin}\theta_2$) and the reflection equation ($\theta_i = \theta_r$), the optical path can be calculated. One of the possible optical paths is shown in Fig. 4(b) [11]. The type 1 prism directs high intensity sunlight deeper into the room but causes a downward harmful glare because all surfaces are inclined. Furthermore, the daylighting area produced by the redirected sunlight would drift due to the varying sunlight elevation angle (Se) during the day.

Based on authors' previously work [11], the authors modified the type 1 prism to an inclined-curved complex microstructure, shown here as type 2. The curved plane is capable of distributing the sunlight into a wide-angle spread of outgoing sunlight,