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Highly concentrated optical fiber-based daylighting systems for multi-floor office buildings

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ABSTRACT

Daylighting is essential for improving indoor environments and reducing electric lighting power consumption in office buildings. Traditional, fiber-based daylighting systems were implemented only on a small scale. To this end, two efficient approaches are presented. The first approach consists of a parabolic trough and the second approach contains a linear Fresnel lens. Sunlight is captured through the concentrator and distributed through the optical fibers. Since it is difficult to achieve a high concentration, a trough compound parabolic concentrator (CPC) is used to pass the maximum captured collimated sunlight into the optical fibers in both approaches. Optical-simulation results have shown that the efficiency achieved in the implemented daylighting systems—which is estimated based on the average illuminance in the interior and on the illumination quality of the system through combining daylight and light-emitting diode (LED) light—is better than that of traditional lighting systems.

1. Introduction

Daylight is used to illuminate building interiors to affect the indoor environment, health, lighting quality, and energy efficiency. In sustainable buildings, daylighting can provide energy reductions through the use of electric light controls, and it can reduce the dependence on artificial lighting, which cannot fulfill the needs of the human body [1]. In terms of health, artificially lit buildings fail to produce comfortable indoor environments. In office buildings, people spend most of their time under artificial light. As a result, 15% of office workers complain of eye strain [2]. The eyes and skin absorb non-visible wavelengths that are needed to synthesize vitamin D3. Daylight can be used to reduce the impact of illnesses such as seasonal affective disorder [2]. Daylight exposure helps to rapidly improve patient recovery and improves worker productivity [2].

Daylighting has a significant role in the field of renewable energy in terms of reducing the use of electricity, which has been significantly increasing in many countries [3]. A reduction in energy consumption and the production of energy through renewable energy sources can lead to a lower production of greenhouse gas emissions, which is becoming an increasingly serious global issue [3]. Buildings, especially office buildings, are the main source of power consumption and greenhouse gas emission, and electricity demand is growing by 0.7% per year in buildings in the USA [3]. It has been estimated that energy consumption in residential and commercial buildings is nearly 40.40% of the total energy consumed in the USA [4]. Therefore, more attention has been paid to energy consumption in buildings, where lighting is the major source of energy utilization. Energy consumption due to electric lighting in buildings is approximately 40–50% of the total energy cost [5]. One of the reasons is that the growth of lighting demand is increasing due to rising average illuminance levels in buildings, especially in newly constructed buildings. Therefore, sustainable buildings have been developed. One of the principles of sustainable buildings is to illuminate the building by daylight instead of artificial light at all times of the day to reduce the overall energy consumption of the building. Efficient daylight buildings are estimated to reduce electric lighting energy consumption by 50–80% [6]. Thus, an appropriate daylighting strategy will lead us to a solution to the energy problem.

In sustainable development, the interior of buildings is illuminated by daylight through the windows and the daylighting systems. During the architectural design process, an important consideration is given to daylight accessing the interior of buildings through the windows and the openings. Since buildings usually have windows, light from the windows decreases very rapidly, and interior areas may not have sun exposure. As a result, the illumination is not consistent and some areas may remain dark. According to European Standard, the requirement for the office buildings is to achieve an average illuminance of 500 lx [7]. However, it is difficult to achieve 500 lx at all times of the day through only windows and openings. Therefore, a daylighting system is needed to illuminate all the dark areas of the building during the day with electric lighting controls to reduce power consumption.

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Previously, daylighting systems were developed to illuminate small-scale building interiors. There has been a need to develop a large-scale daylighting system to illuminate large-scale building interiors. In the literature, large-scale, sunlight-capturing systems have been developed for photovoltaic power generation and thermal applications [8,9]. Therefore, new methods must be introduced to use those systems for daylighting. Several concepts regarding daylighting systems have been demonstrated with light pipes [10–13], light guide [14], and optical fibers [15–25], and most of the designs have a large number of tracking reflectors and lenses, and, thus, require a large area in which to be installed.

Usually, daylighting systems are preferably installed on the roofs of building, where sunlight can be captured at all times of the day. One system to be developed was the core daylighting system, which was mounted near the ceiling region [10]. However, it was difficult for the system to track the sun at all times of the day. It was difficult to install the system due to the different structural designs of buildings. The system was only able to illuminate the building interior for half a day. It had two models with different capturing systems using small Fresnel lenses and flat reflectors. The sunlight was captured through concentrators, guided through light pipes, and distributed through a light guide. The light guide was made of prismatic optical film with 99% transmittance and reflection and a multilayer optical film with 97% reflection. The efficiency of the system was better than that of previous light pipe-based daylighting systems. The energy performance of the system was calculated through simulation, where a 40–57% energy saving for lighting through windows and the daylighting system was achieved [26]. One of the disadvantages of the system was that the light levels decreased as soon as the distance increased from the wall where the system was installed. Therefore, it was not able to achieve uniform illumination for large-scale building interiors.

A currently available daylighting system using optical fibers is the Himawari solar lighting system [16]. The system consists of a sun-tracking device to capture direct sunlight all day. The light is focused through a Fresnel lens, and only visible light is inserted into optical fibers. It has two series of models with a different number of lenses and optical fibers in the bundle. All models contain quartz-glass optical fibers (QOFs), which exhibit low losses during light transmission. However, the system is costly due to the price of QOFs. The system combines six optical fibers in each bundle for light distribution, and the illumination angle from the fiber bundle is 58°. The luminous flux per cable is 1920 lm. Overall, the light capturing and distribution method is not well defined in this design in terms of it achieving uniform illumination. The system was designed only to illuminate small-scale building interiors.

The idea of capturing high-intensity sunlight has been demonstrated in which a parabolic dish concentrated sunlight into a single optical fiber through a flat mirror [17]. For light transmission, fused-silica optical fibers were utilized. The optical fiber had a diameter of 1 mm, and the parabolic dish had a diameter of 0.2 m. After reflection of the light at the parabolic surface, most of the light was lost through it hitting the outer surface of the optical fiber. As a result, most of the light was not able to reach the flat reflector. Many small parabolic dishes were used to collect sunlight. However, the large number of parabolic dishes occupied a large area. Each parabolic dish needed a separate sun-tracking module, which increased the cost of the system. The system was used for solar thermal applications to produce energy rather than daylighting. For daylighting, a system should contain a minimum number of concentrators. Therefore, this approach is not suitable for installing the concentrators on the roofs of buildings. If a fiber bundle is used instead of a single fiber with this approach, uniform illumination will not be obtained, even with a very high concentration of light.

Two common approaches to fiber-based daylighting systems seem suitable: the parabolic reflector and Fresnel lens. A parabolic dish-based approach was presented for optical fibers [27]. Sunlight was concentrated through a concave parabolic reflector, and then focused onto the bundle of optical fibers through a second, concave parabolic mirror. The diameter of the second reflector was larger than the diameter of the fiber bundle, and the optical fibers in the bundle were not well arranged. Large inter-fiber spaces were present in the fiber bundle. Due to the spaces between the fibers, most of the light was lost, and the illumination on each fiber-surface end was not uniform. As a result, uniform illumination was not achieved in each fiber. They did not highlight the losses due to the mechanical components that absorb sunlight before it enters into optical fibers. A Fresnel lens-based approach was studied using optical fibers [20]. The researchers did not manage to insert the maximum level of sunlight into the optical fiber bundle; however, they achieved uniform illumination from each fiber in the bundle.

We analyzed losses and improved two fiber-optic daylighting systems using a parabolic reflector and Fresnel lens through simulation and real experiments [23]. During the development, the efficiency of the system was improved via uniform and collimated illumination on the fiber bundle and by reducing the heat problem, which had critical importance for the plastic optical fiber (POF) to make the system cost effective. The parabolic dish and Fresnel lens had a diameter of 320 mm and 300 mm, respectively. The light was focused on the fiber bundle, which had 55 and 54 optical fibers for the parabolic dish and the Fresnel lens, respectively. Illumination uniformity at the distribution stage was also improved through lenses. Recently, the need has been to illuminate a large number of optical fibers. As soon as we increase the optical fibers in the bundle, we need to increase the size of the concentrator. Therefore, we need a large parabolic reflector and Fresnel lens, which are difficult to manufacture.

In [13], they analyzed daylight levels inside a lecture room using a light pipe and fiber-optic solar dish through simulation. Sunlight entered into the light pipe through a transparent dome cover. A solar dish tracked the sun all day to capture direct daylight. It was demonstrated that more daylight can be harvested through the tracking-dish concentrator for solar altitudes of less than 50°, and a greater number of lumens was available for the light pipe at a higher solar altitude. Furthermore, it was found that tracking-dish concentrator gave high illuminance uniformity at different solar altitudes than that of the light tube.

The main purpose of this study is to achieve uniform light into the optical fibers and to deliver it to large-scale building interiors. Consequently, two novel approaches are proposed for the parabolic trough and the linear Fresnel lens. For the parabolic trough, sunlight is concentrated and focused toward the parabolic reflector, and then collimated light is transmitted toward the trough compound parabolic concentrator (CPC). For the linear Fresnel lens, concentrated light is collimated through the plano-concave lens and then light enters into the trough CPC. Previously, it was not possible to achieve high concentration through the parabolic trough and linear Fresnel lens for the optical fibers. We introduce the trough CPC to solve the issue of high concentration for the optical fibers. After the trough CPC, a linear array of optical fibers is positioned for both approaches. To make the system cost effective, POFs were used for most of the transmission. They are very sensitive to heat. Therefore, we used silica optical fibers (SOFs) before the POFs to reduce the heat problem. The proposed system is advantageous because it is expandable, whilst only requiring one tracking module. It can be expanded by increasing the rectangular aperture height and width of the parabolic trough. If the rectangular aperture height is increased, optical fiber arrays will be increased. In the same way, more fibers can be added in the single array by increasing the rectangular aperture width. Likewise, the system using the linear Fresnel lens can be expended by increasing the width and length of the linear Fresnel lens. Therefore, the required design can be