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Design and development of a faceted secondary concentrator for a fiber-optic hybrid solar lighting system

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ABSTRACT

Fiber-optic solar hybrid lighting for mobile application such as military shelters in remote areas is appealing since high initial costs of such systems appear to be justified. This paper addresses the aspect of two-stage optics for a fiber-optic solar lighting system for the mobile application. More specifically, the focus of this paper is on the design and development of a second stage or secondary concentrator. Two-stage optics offers a distinct advantage of higher sun angle tolerance and hence a low-accuracy tracker can be used for the mobile application. The objective of this study was to design and develop a secondary concentrator that yielded a minimized peak illuminance on the fiber-optic inlet and achieved uniformity, to avoid localized heat damage to the fiber inlet. In addition, the overall goal was to increase the lumen output from the two-stage optics. Specifications for the design of the two-stage concentrator were: (1) the primary stage concentrator was a 10-in. diameter Fresnel lens; (2) solar tolerance angle or the half-angle of acceptance was ± 1.75°; (3) the fiber half-acceptance angle was ± 40°; and (4) the fiber optic cable diameter was 0.5-in. Raytracing was used to determine the optimum geometry for the secondary lens. Among various geometries simulated included a conical secondary, a Compound Parabolic Concentrator (CPC), and a combination of conical and Compound Elliptical Concentrator (CEC). The analysis showed that a combination design comprising conical/CEC geometry was better than the conical and CPC geometries in terms of greatest overall light output and most reduced peak illuminance on the fiber optic cable. Prototype secondary lenses based on the design were fabricated from acrylic and optical silicones. Testing of the prototype lenses revealed that acrylic secondary performed better than the silicone lenses in terms of the measured lumen output. Testing also showed that the fiber-optic cable temperature was within the maximum operating temperature of acrylic and didn't suffer any high temperature damage during the five month long outdoor testing.

1. Introduction and background

More than 4 quads of energy is used annually in the US in providing ***artificial lighting*** for buildings, which costs about ***$40 billion.*** While some of this lighting is needed in the early morning or late evening hours, most of the electric lighting is used during daylight hours. There is an opportunity to save at least half of this energy considering cloudy periods and nighttime. Even though conventional daylighting employing windows and skylights has helped reduce electricity use, it cannot take full advantage of sunlight. For buildings that have a large area-to-perimeter ratio and more than one floor, skylights and windows are not useful for daylighting much of the building, since many rooms will be too far from exterior walls or the roof.

A promising alternative to conventional daylighting systems is to transport sunlight deep inside a building using optical fibers. More than a decade ago, Gorthala (Flynn, 2001) built a prototype passive fiber-optic daylighting system (U.S. Patent No. 6299317) that incorporated a sunlight collector with a primary and a secondary concentrator in tandem, plastic optical fibers and a passive dual-axis solar thermal tracker (see Fig. 1). Prior to this effort, Himawari, a Japanese fiber-optic daylighting system was developed in the 1980s but didn't achieve any market penetration due to its high cost. It employed Fresnel lenses and high-cost glass optical fiber. However, it appears that Himawari (2014) is still alive as evidenced by a marketing catalog. Then came the Hybrid Solar Lighting (HSL) technology (parabolic collector based) that was developed at Oak Ridge National Laboratory (Muhs, 2000). That technology was licensed to Sunlight Direct LLC, but there is no commercial product available from this company. Parans (Hallqvist, 2011),

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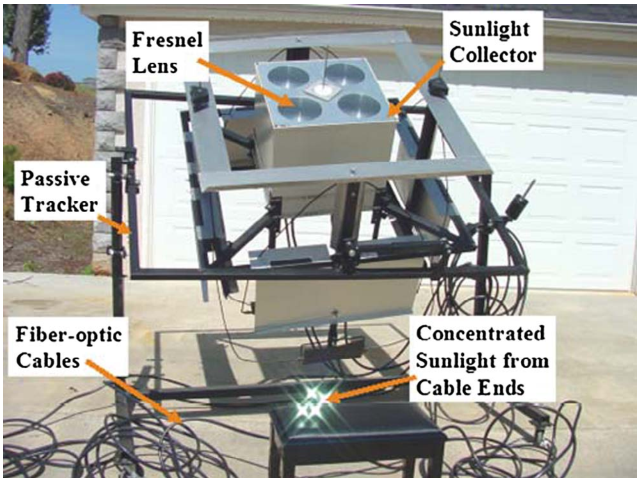

Fig. 1. A passive fiber-optic daylighting system prototype developed in 1998–99 by Gorthala (Flynn, 2001).

a Swedish company, started developing and currently marketing Fresnel lens-based technology.

With the emergence of highly efficient, low-cost and reliable LED lighting technology, the fiber-optic daylighting technology with a high initial cost may never become economical to achieve successful commercial market penetration. However, one promising application for the fiber-optic daylighting is mobile military shelters. The cost of fuel including delivery of fuel to military operational areas can be very high, ranging from \$15 per gallon to \$400 per gallon depending upon the location and whether force protection is required for the supply convoys. Therefore, the US Department of Defense has been adopting renewable energy technologies for military shelter application, and the development of ruggedized, fiber-optic daylighting has been identified as a potential technology. The present effort has been on the design and development of hybrid, fiber-optic, daylighting technology suitable for the mobile military shelter application. A schematic of the hybrid lighting technology being developed is shown in Fig. 2.

As shown in Fig. 2, the hybrid lighting system comprises a sunlight collector, a tripod structure with a tracker, fiber-optic cables and a hybrid light fixture. Non-imaging optics is a critical element of a sunlight collector. Two types of optics have been proposed in literature for fiber-optic daylighting application – (1) reflective (Muhs, 2000) and (2) refractive (Himawari, 2014). Two-stage optics have been used for concentrating light in many applications ranging from concentrating photovoltaics (CPVs) (Chen and Ho, 2013; Bonitez et al., 2010; Ning et al., 1987) to lasers (Abdel-Hadi, 2005; Liang and Almeida, 2011) to space solar thermal propulsion systems (Soules et al., 1997). In the two-stage optics, the primary concentrator can be either reflective or refractive. Similarly, the secondary concentrator can be either reflective or refractive and the refractive secondary can also be totally internally reflecting (TIR).

Gorthala employed a two-stage concentrator for the fiber-optic solar lighting system as shown in Fig. 3. As shown in Fig. 3, the two-stage concentrator consists of an 8-in. diameter Fresnel lens as the primary stage and a conical TIR lens as the secondary stage. Also, another study (Nakamura and Senior, 2008) utilized a parabolic primary and a quartz TIR secondary for producing solar thermal power for lunar materials processing. Parans system (Lingfors and Volotinen, 2013) employed small 6.5 cm by 6.5 cm Fresnel lenses as primary concentrators plastic optical fiber. The system didn't use secondary concentrators. However, the accuracy of tracking is unknown. It used UV-IR filter to prevent fiber damage.

The measured output efficiency was only 19% for a 10-m long fiber. Another study (Sansoni et al., 2007) evaluated several concentrators for fiber-optic illumination. It included three different classes of optical systems - collectors with spherical surfaces, parabolic concentrators and concentrators with aspherical surfaces. One promising design comprised a catadioptric system with a single block of quartz and silica fibers. Because of cost considerations, they further developed a system with PMMA aspherical lens and plastic optical fibers. These systems utilized sophisticated electromechanical tracking system to accommodate the sunlight within 0.5° acceptance angle. There was no discussion on thermal management of plastic fibers. The lens diameter was also small (5.6 cm). In a recent study (Ullah and Whang, 2015), a parabolic reflector (diameter 36.0 cm) with a collimating lens for fiber-optic daylighting was analyzed. In a preemptive effort to mitigate the thermal problem, they utilized silica fibers in the beginning and plastic fibers for transmission of light. One concept (Shen et al., 2009) with a large Fresnel lens (35 cm by 35 cm) incorporated an optical coupler that integrated both sunlight and LED. The coupler consisted of a plastic CPC and an additional CPC secondary. It also had a feature to use photovoltaic cells to produce electricity when there was no need for lighting in the building. However, no discussion on inlet tolerance angle for the Fresnel lens or tracking accuracy or the performance of the system. Also, there was no discussion on thermal management of plastic optical fibers. Tekelioglu and Wood, (2003) were the first ones to address the issue of burning of plastic optical fibers in the fiber-optic daylighting system that used a large diameter (100 cm) parabolic concentrator. Their thermal analysis indicated that adding a fused quartz glass attachment to the plastic fibers.

More serious problems with a large diameter (100 cm) reflective concentrator system having plastic optical fiber for fiber-optic

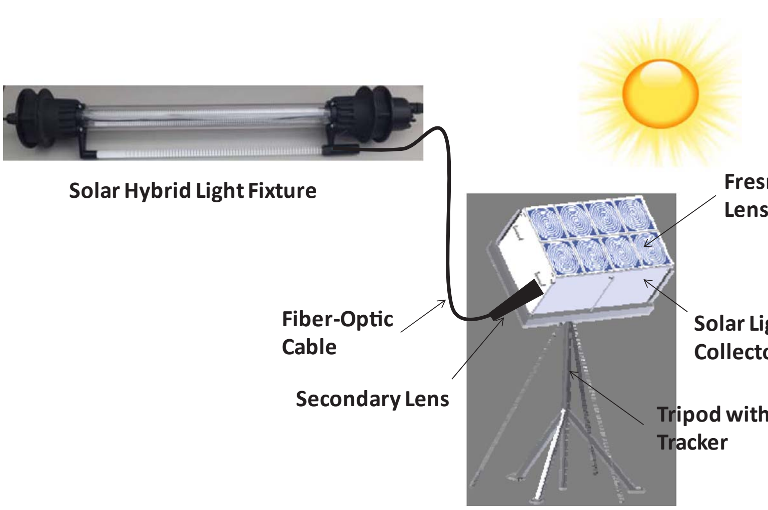

Fig. 2. A schematic of a fiber-optic hybrid solar lighting system for mobile application.