Applied Mechanics and Materials Vol. 492 (2014) pp 101-105
Online available since 2014/Jan/09 at www.scientific.net

doi:10.4028/www.scientific.net/AMM.492.101

Analysis of plastic optical fiber based daylight system suitable for building applications

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Keywords: Building Energy Efficiency, Daylight harvesting, Plastic Optical Fibers, Solar tracking

Abstract. In the scenario of world energy crisis, building energy efficiency has become a mainstream research focus; since buildings take up a large share of the world energy consumption. Lighting plays an integral part in the building's operationality through providing indoor visual comfort; and the much-needed daylight harnessing in building structures can be achieved through various strategies. This paper aims to evaluate the amount of plastic optical fiber (POF) required for achieving optimum indoor illumination through light transport and study the advantage of two dimensional solar tracking and light concentration on indoor daylight enhancement through POF as a trade-off for the amount of POF required in a static system. Illumination attained inside a representative closed chamber due to light transported by POF via various mechanisms was experimentally compared with outdoor direct illumination and the amount of POF required for achieving comfortable indoor illumination was calculated for a proposed system involving tracking and light concentration. A microcontroller based dual-axis solar tracker was designed for tracking sunlight on the POF collector node every 10 seconds and opaque internally reflective plastic containers acted like sample rooms in a building. Calculations for the representative day normalized for the flooring area in an office building showed a promising payback period of around 5 years through partial replacement of electric lighting. Additionally, reduction in heat conduction through window glazing further reduces the cooling costs.

Introduction

Buildings, both residential and commercial, account for as high as 40% of world's energy consumption [1] and 37% of the total energy consumption in India [2]. Global focus is shifting towards considering energy saving and carbon emission reduction as a top priority while designing buildings. With the windows contributing up to 60% of the total energy loss of a building, fenestration alternatives have a huge potential to provide large energy savings [3]. Conventional window glazing has a higher thermal transmittance than the opaque sections thus accounting for substantial amount of energy losses and increasing costs towards HVAC.

Windows also serve as openings to external environment by allowing daylight to enter building structure. By facilitating vision, lighting has a vital positive effect on people because it provides added sense of cheerfulness and brightness [4]. Lighting also affects the basic biological functioning through its effect on human bio-rhythms [5]. Using electric lighting as net alternative to external daylight has many drawbacks. Electric lighting is one of the peak global end usages of electricity [6]. In typical office buildings, it accounts for 30-50% of the total electricity consumption [7]. Additionally, through getting heated up, these may add to the cooling costs. Also, by using daylight inside the facility, only about 20-50% of the heating is caused as compared to that caused by equivalent artificial lighting. This significantly reduces the building cooling load.

Through natural selection, the human eye is best suited for natural light; Daylight is a kind of light source that matches closely with the human visual response; as such its quality is as high as to be the best for color rendering [8]. Sunlight has luminous efficacy of around 110 Lumens per Watt, while the values for CFL lamps and incandescent lamps are around 75 Lumens per Watt and 20 Lumens per Watt, respectively. This makes optimum compatibility of daylight with human response level. Light tubes [9] and Optical fibers could be used for transporting external daylight inside the building structures as a partial replacement to electric lighting without adding much to the heat load. Fiber optic cables have been used since early 1990s in remote-source lighting systems; a technology where light travels through fiber optic from its source to one or more remote points [10]. High cost of fiber optics and great attenuation in POFs were the major hindrances in practical usage of fiber optics, but the development of graded index POFs in 1990 and the later advances in the low-attenuation per-fluorinated fibers in 1996, have helped POF emerge as a more feasible alternative to light tubes and a cheaper and flexible alternative to glass optical fiber through the capabilities of smooth bending; resistance to vibrations and wall ducting capabilities [11]. The feasibility of using POF for daylight transport is still challenged by high costs of signal transmission grade POFs; and dedicated supply of cheaper grade POFs has the potential to substantially cut down the payback period of these retrofits. With POF accounting for the major initial investment for the retrofits, solar tracking and light concentration provide the possibility of decreasing the amount of POF required for achieving desired levels of comfortable indoor illumination of 450 lux. This paper aims at determining the amount of optical fiber required towards daylight transport for achieving comfortable indoor illumination.

Material and methods

Optical fiber based light transport system was constructed as shown in Fig. 1. A two dimensional tracking system using LDRs and Arduino Uno microcontroller powered by 5V DC servo motors was constructed to rotate the collecting nodes of the POFs (low grade, POF bunch acquired from optical fiber based toys, ₹16 for 1 sq. cm x 25 cm length) in two axes. With the normal of the nodes tracking the sun, these POFs transported light to create illumination inside opaque chambers. These chambers were made by lining similar plastic containers with silver foil to make them opaque and internally reflective; and thus act as a sample room inside a building. To evaluate direct benefit of the tracking assembly, a 3V photovoltaic panel was mounted on the tracker and its peak power values were compared with a similar static panel kept on horizontal plane at various time intervals.

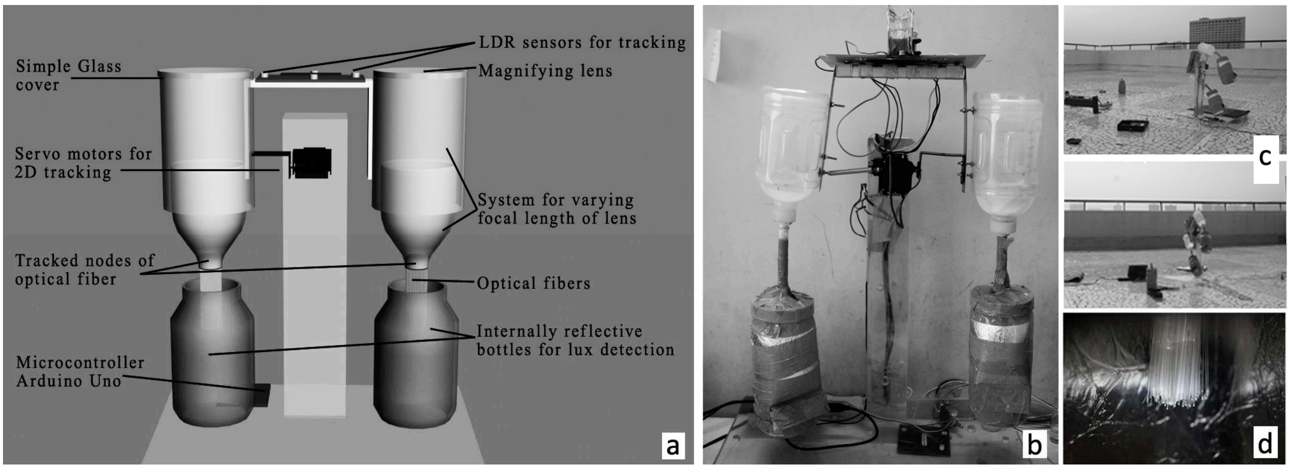

Fig. 1 (a)Concept, (b)fabrication and (c)experiments with the dual axis solar tracker for the optical fiber based light transport system. The containers represent sample rooms inside a building. (d) illuminated ends of POF in the container

The tracking was designed using four Light Dependent Resistors (LDRs) as detectors to sense the motion of the sun. The difference in the intensity between the signals transmitted by the LDRs through the microcontroller directed the servo motors to turn accordingly. Sensor assembly involved microcontroller Arduino Uno, 5 mm LDRs, 330 Ω resistances and potentiostats.
The tolerance value was set at 30 Ω to make the sensitivity optimum and delay time was set at 10 seconds keeping in mind the slow change in the sun's angle. During the dawn to dusk testing, the illumination values attained at a distance of 2 cm from the emitting nodes of the POF were manually recorded using the lux meter every fifteen minutes at various positions: at the

unobstructed horizon (L_T); diffuse illumination attained on a horizontal surface (L_D); at an unobstructed plane normal to the sun (L_T- L_D), inside the static container with exposed POF node normal to the horizon (L_s), inside the container with the node tracking the sun (L_t) and inside the container with the node tracking the concentrated sunlight at 9x concentration (L_{ct}). The PV mounted on the tracker was compared with the similar PV on a horizontal plane by taking readings every 15 minutes from dawn to dusk. The node of tracked optical fiber system was kept normal to the sun through the test period, and the illumination attained at a distance of 2 cm from the end of the fiber inside a closed container was obtained using a digital lux meter [Qingdao LX1010B, China]. The tracking system was designed for two tracked optical fiber nodes facing the sun, one with a glass capping and the other with a magnifying lens of ~9x concentration ratio. There was a sliding mechanism designed to vary the concentration ratio of the system by changing the lens position towards/away from the optical fiber node.

Result and Discussions

The merit of the tracker was determined through comparing the peak power PV characteristics of the PV module on the tracker (continuously facing the sun) with that of the static PV module (lying on the unobstructed horizon) through the sample days. This was done also for balancing out the frequent cloud shading effects in the illumination measurements. Between 11 am to 1 pm, the overhead position of the sun was equally suitable for static systems as such reduction in the relative power advantage of tracking was observed. During fore-noon and evening period, advantage of tracking on the peak power characteristics was dominant.

Fig. 2 compares the variation in illumination attained inside the containers for various permutations of the tracked-concentrated designs with illumination at the open horizon (through beam component of radiation) as well as the variation in the peak power values at the tracked v/s static PV modules. The illumination in the tracked-concentrated system was compared with the illumination attained at the horizon and was challenged by the quality of the POF used and the cloud cover on the experimental days. Due to the extremely narrow angle required for direct intake of radiation, the relative advantage of tracking on illumination dominated through the day. Employing the data of the values obtained experimentally for L_T , L_d and L_{ct} , an interface was designed to determine the amount of optical fiber surface at the receiving node for the tracked-concentrated system.

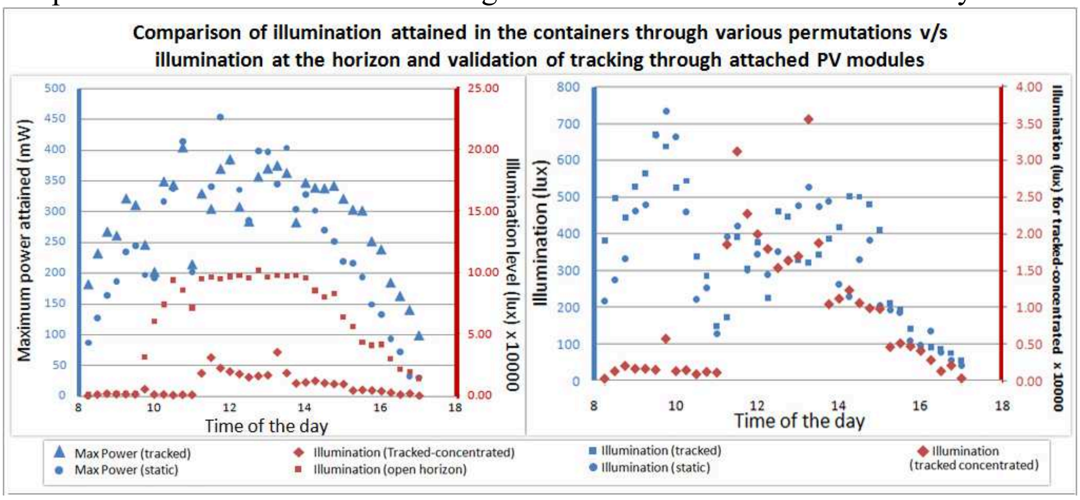

Fig. 2 Illumination attained inside/outside the containers for various permutations and PV modules peak power values through the day: comparison between static, tracked and tracked-concentrated systems

For room with existing windows; the illumination calculation via windows at any reference point was calculated according to Eq. 1

$$\text{Illumination}_{beam} = ([L_T\text{-}L_D].(\text{Cos}\theta/\text{Cos}\theta_z).A_w.\ \tau_r.)/(2.\pi.r_{ref}^2)\ . \qquad (1)$$

Here τ_r is the transmissivity of the glazing material, L_T and L_D are the lux values obtained at the lux meter in lumens per square meter for total and diffuse light, θ is the angle between the sun and the window's normal at that time, θ_z is the angle between the sun and the horizontal surface at that time. r_{ref} is the distance of the reference point from the centre of the window and A_w is the defined area of the window.

$$Illumination_{Diffuse} = (L_D.A_w.0.85*DLF) . \quad (2)$$

Here DLF was the daylight factor computed at the reference point as the amount of sky hemisphere visible at the reference point as shown in Eq. 3

$$DLF=A_w/2.\pi.r_{ref}^2 . \quad (3)$$

For the room divided into 25x25 segments, the value of r_{ref} for the individual elements was defined through Eq. 4

$$r_{ref} = ((window\ position + window's\ width / 2)*i/25)^2 + ((length\ of\ the\ room)*j/25)^2 . \quad (4)$$

Here i and j were the representative numbers for the position of the element in the room taken up for the sequential calculations. The illumination attained from the POF at the reference was calculated from the L_{ct} value according to Eq. 5.

$$Illumination_{POF} = Average\ \{L_{ct} .(0.02/Distance\ from\ emitter\ at\ ceiling)^2\}. \quad (5)$$

The computed values for the illumination (beam and diffused) through the windows and that through the POF installed at the room's ceiling are shown in Fig. 3. Also, the figure shows the regular and logarithmic plot for illumination through existing windows.

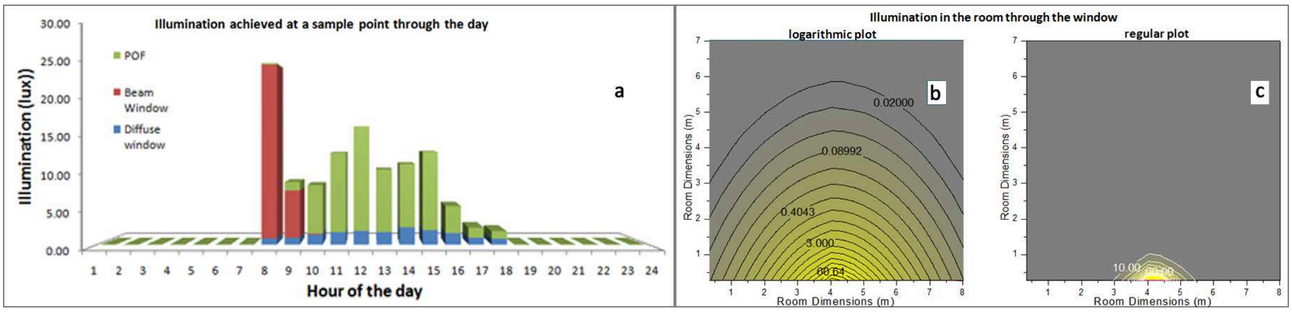

Fig. 3 Computed values for illumination for a sample day (a) averaged hourly values through window and POF light transport system (b) logarithmic plot and (c) regular plot of the window illumination at the sample hour (15 Jan at 9 am) for each point in the room

The amount of illumination required from the POF at every individual point was computed from the difference between the required adequate average illumination of 450 lux and that supplied through the existing windows. The ratio between the excess requirement and the illumination provided by input amount of POFs gave the required amount of POFs at the collecting node for illuminating the sample room. For the sample calculations, the insights were as follows: Daylight factor at the room's end through windows: *0.0038 (0.38%),* Average lux for the room (direct and diffuse) through windows at the computed hour (Jan 15 at 9 am): *1.6 lux,* Average lux at reference point contributed by the POF ends at the ceiling (complementing the window illumination): *10.82* lux/cm^2, concentrating area factor needed at the tracker for adequate average illumination of 450 lux (neglecting attenuation factor): *6.56 (6.56* cm^2*), Amount of POF needed for the sample room per square metre flooring at the collector node: 6.56* cm^2, energy saved by replacement of electric light with daylight for this facility: *270 Wh per day.*
Further analysis showed the following inferences: Normalised savings (through replacement of electric lights) normalised to per square meter flooring per year: *₹45.33/sq.m*. Normalised cost of high grade POF (lifetime = 10 years): *₹1,158/sq.m.* Tracker's installation and operation-and-

maintenance costs: *₹141.12/sq.m.* Normalised Annual CO_2 savings (after incorporating the heat load of the electric lights and the cooling load required to remove excess heat through fenestration: *220 kgs/year*. Payback period for the retrofitting through daylight integration: *29.07 years*, payback period when using low grade POF: *5.07 years.*

Summary

This work focused on the experimental data collection and further theoretical assessment of the concentration cum tracking based daylight enhancement system using POF light transport systems; as a complementary design for existing daylight integration systems and partial-to-total replacement of electric lighting. The optimum amount of POF required for a sample room was determined depending on the room's size; existing window's orientation and area; height of the ceiling and the glazing material at the window. The payback period was calculated for a sample room and was assessed to be in the promising range of 5.07 years. This promising technology; for further growth needs to overcome the basic challenge of reducing the price of low grade POF through dedicated supply and large production; since cost of the available POF is the major share of the investment in these daylighting retrofits.

Limitations of the study and scope for future research

The amount of POF required for illuminating a given sample room was determined based on the results of simulations specific for a sample day and lacks yearly average illumination. Also, optical aberration in POF was neglected; which becomes substantial with increase in POF length. Future research may include lengthwise optical aberration (considering usage for varying distances in high-rise buildings) and calculate the optimum amount of POF on annual average basis thus determining system feasibility based on the payback options.

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