A Study on Waveguide Performance of Luminescent Solar Concentrators

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Abstract

Luminescent solar concentrators (LSC's) are evolving cost-effective organic methods for trapping solar energy using the fluorescence property of organic dyes. The study aims in finding a waveguide design for LSC, in different waveguide materials, PC and PMMA in varying dimensions filled with solution of anthracene in heptane with minimum losses. By comparing the output responses, the LSC with the waveguide design of 6 cm x 3cm x 5cm made of the PMMA (3mm thick) is observed to trap more incident radiation than the unaided solar cells. The maximum output current is measured to be 6.10 mA for a source of 40W power which is convincingly higher than 3.21 mA obtained from the unaided solar cell measured with the same source.
Keywords: Luminescent solar concentrator, liquid dye, anthracene, fluorescence, cuvette geometry, PMMA

I. INTRODUCTION

Luminescent solar concentrators (LSCs) are emerging, non-conventional solar energy tracking systems to aid the photovoltaic cells (PVC) that replace complex simulation techniques. As the name suggests, LSC's are slabs made of organic dye(s) embedded in polymer sheets that absorb both direct as well as diffuse solar radiations and re-emit at a larger wavelength on to a solar cell attached to the ends [1]. By trapping radiation in this way, the expense of using a large number of PV cells is significantly reduced. Besides the technique allows the abundant UV-Visible wavelength window from the sun, available to the PV cells for which they are originally transparent to [2]. Although the idea was conceived three decades ago by Goetzberger's and Weber's team workers, the prospects have been stunted due to the challenges involved in minimizing the losses in the design [3] & [4]. An optimum design of LSC enables effective trapping of radiation and directs to the solar cell/wafer through absorption and re-emission mechanisms similar to total internal reflection within a rectangular slab or a cuvette in the present case.

An indigenous design of a LSC employs in reducing losses like, (1) unabsorbed radiations, (2) surface reflection and (3) escape cone losses [5] & [6]. Among the above criteria, major loss factor associated with is the escape cone loss, where, the incident angle is lesser than the critical angle ($\theta_c = sin^{-1}(1/n)$) for dye excitation. The next important factor in improving the efficiency is the choice of an appropriate dye with a high quantum yield, large Stoke's shift, long absorption range and high photo-stability for longer exposures to sunlight and environmental effects [7]. In regard of the host polymer, previous studies have suggested polymethylmethacrylate (PMMA) to be the most suitable candidate for the matrix/waveguide for its low cost, optical clarity, photo-stability and long wavelength absorption [8]. Polycarbonate (PC) is an equally suitable candidate as well as easily available with a kin refractive index as PMMA. In the choice of a fluorophore, we chose a simple polyaromatic compound with three fused benzene rings called, anthracene in heptane solution for its broad absorption range and spectral sensitivity [9].

In the present study, different LSC waveguides have been designed using 0.6M solution of anthracene in heptane solvent and their output responses have been studied for two polymer materials (PMMA and PC) and cuvette dimensions.

II. MATERIALS AND METHODOLOGY

The required polymer, PMMA of 99% purity was purchased from CIPET, Chennai, with 3 mm thickness whereas PC of 1 mm thickness is obtained from locally available water containers. High grade photovoltaic cells with a maximum voltage output of 1.9V were used to study the output response to incandescent bulbs of power output 60W and 40W. The two rectangular waveguides were fabricated with dimensions, (1) 10 x 5 x 2 cm using PC and (2) 6 x 3 x 5 cm using PMMA. After filling the waveguides with the 0.6 M solution and neatly sealing with a PV at one end, the current and voltage responses were studied at different distances from the source (fig. 1).

The absorption and emission spectra of anthracene in heptane were obtained from a U-2001 HITACHI UV-Visible spectrophotometer with tungsten iodide and deuterium lamp source (range 190 nm to 800 nm) and a SL174 spectrofluorometer with a 150W xenon arc lamp source, respectively. Considering the two prominent absorption peaks in figures 2 and 3, the spectra show a Stoke's shift of nearly 70 nm, with a quantum yield of 0.43.

III. RESULTS AND DISCUSSION

Figures 4 and 5 show the output voltage and current variation of the first waveguide with respect to its distance from the source. As can readily be seen, the waveguided PVC is less sensitive to the incoming radiation than the unaided one. Although the thickness of the polymer is only 1 mm, with a surface area to volume ratio (S/V) of 1.8 cm^{-1}, the response is trivial. A significantly weak response exists even after increasing the intensity of the source to 60W (figs. 6 and 7). This depicts that geometric losses are more pronounced at this cuvette dimensions, that hinders effective absorption and emission of the fluorophore thereby sufficing the efficiency of the solar cell. Also the difference in the outputs broaden with larger distance, indicating that most of the incoming radiations are lost unabsorbed which suppresses the probability of total internal reflection. A substantial contribution to this suppression here is due to the existence of non-radiative decay losses that occur due to heat transfers. Thus, while taking this into account, the S/V of the next cuvette is slightly lowered.

In view of the geometric losses posed by the PC waveguide, the PMMA (3 mm thickness) waveguide with a slightly smaller surface area to volume ratio of 1.4 cm^{-1}. As suggested in previous studies [10], achieving a smaller S/V ratio reduces the heat losses within the solution which enhances the tracking efficiency more than mirrors and lenses. As seen from figures 8 and 9, the response of the waveguided PVC is noticeably higher than that of the unaided. By analysing the voltage, there is a prominent variation with distance in figure 8. A significant leap in the charge emission as high as 3.2 mA is also evident from figure 9, which is inevitable for a solar cell's performance. The results show that by increasing the thickness of the cuvette, it is possible to concentrate the diffuse light onto the cell in addition to the direct radiation. By using an appropriate fluorophore in conjuction with a suitable polymer [11], the energy of the photons reaching the solar cell which is originally in the range of 1.2 eV to 3.1 eV is shifted to the infra-red range as suitable for the Si cell's responsivity. Inspite of its non-unity quantum yeild, the chosen fluorophore serves as an active candidate due its large Stoke's shift by minimizing re-absorption losses. The choice of PMMA provides the total internal reflection pathways due to its desirable refractive index, $n = 1.49$, by the minimising escape cone losses.

IV. CONCLUSION

The overall observations infer that a 3 mm thick PMMA sheet is an ideal choice for a host in LSC's for fluorophores with large Stoke's shift. While designing a cuvette to hold liquid dyes, the S/V ratio plays a crucial role in minimising the non-radiative decay losses. A fluorophore with a larger Stoke's shift reduces reabsorption losses and enhances total internal reflection. The study offers a preliminary understanding on the performance of a PVC in the UV-Visible range with a liquid carrier molecules. With further challenges to overcome, like lifetime, temperature dependence, etc., the advancements in mixed/complex dyes, quantum dots, hybrid polymer materials and hybrid photovoltaics keeps opening newer possibilities in achieving an effective LSC design.

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VI. FIGURES

Fig. 1: Schematic representation of the experimental set-up

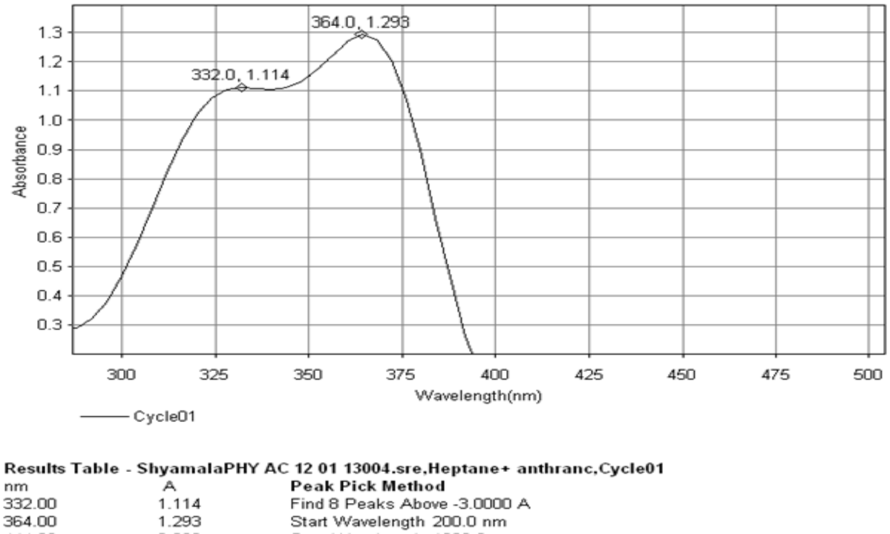

Fig. 2: Absorption spectrum of 0.6 M solution of anthracene in heptane

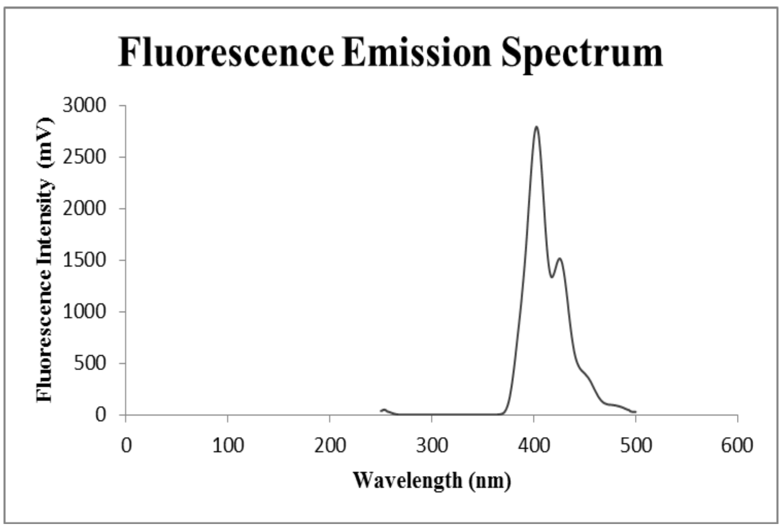

Fig. 3: Fluorescence emission spectrum of 0.6 M solution of anthracene in heptane

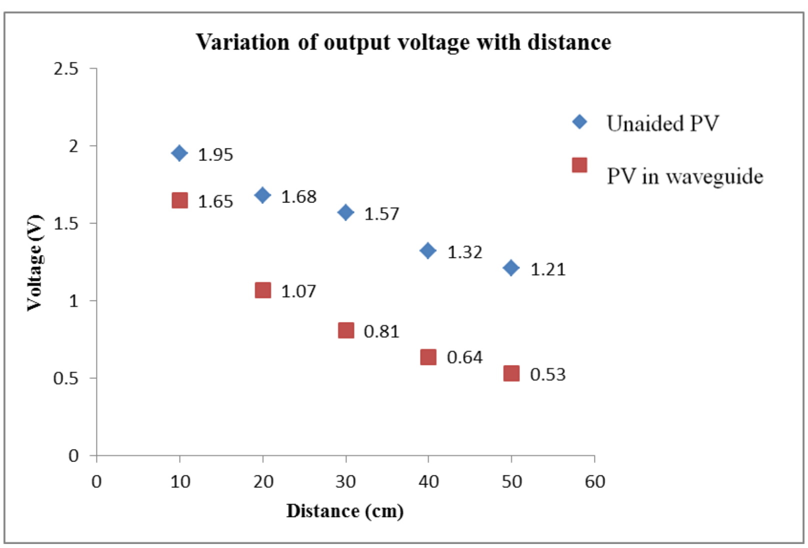

Fig. 4: Comparison of voltage response of unaided and waveguided PV for 40W source

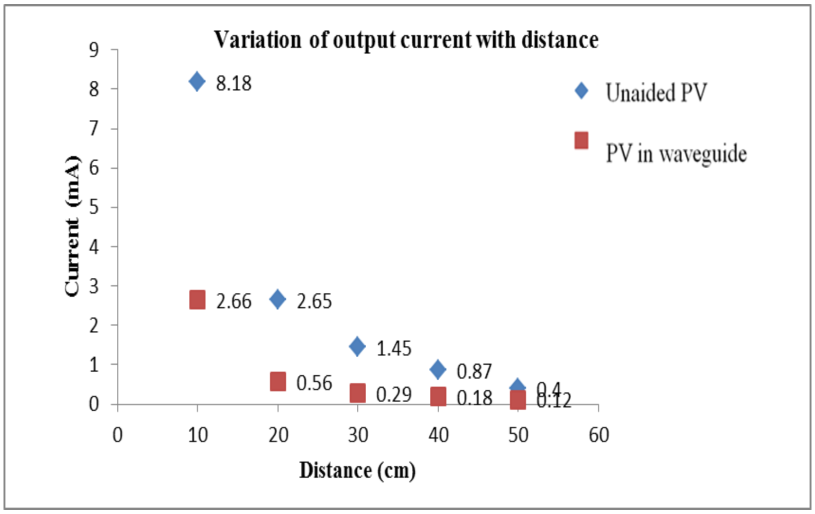

Fig. 5: Comparison of current response of unaided and waveguided PV for 40W source

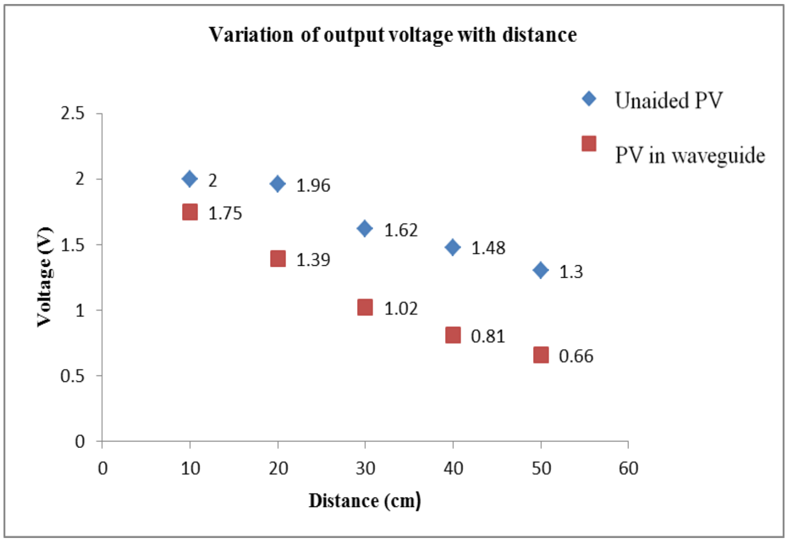

Fig. 6: Comparison of voltage response of unaided and waveguided PV for 60W source

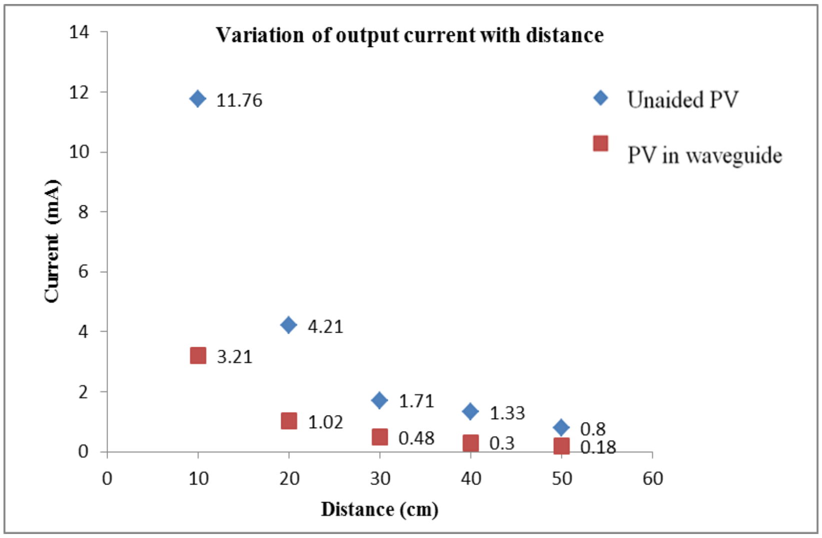

Fig. 7: Comparison of current response of unaided and waveguided PV for 60W source

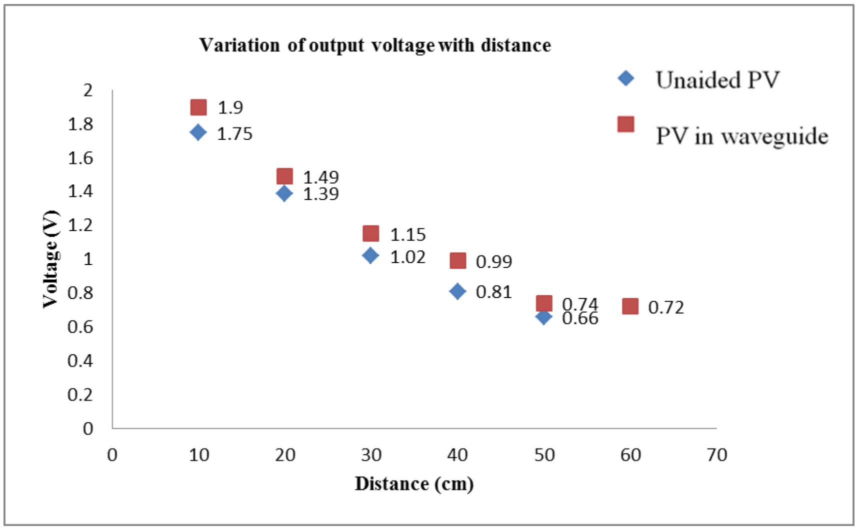

Fig. 8: Comparison of voltage response of unaided and waveguided PV for 40W source

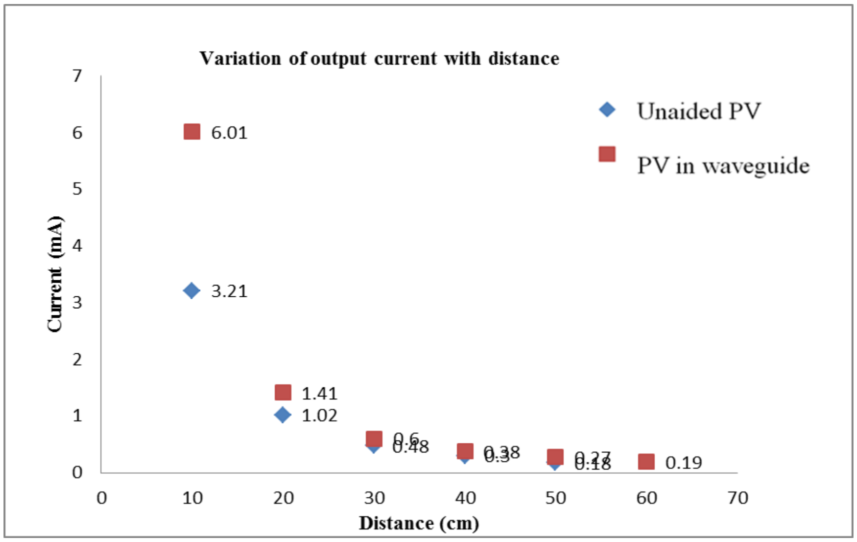

Fig. 9: Comparison of current response of unaided and waveguided PV for 40W source

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