RP Current Trends In Applied Sciences
Vol. 3, No. 3 (July – September 2024) pp. 51–55
e-ISSN: 2583-7486

Cite this article: Anugop B, Lakshmi Srinivasan, Kailasnath M, Dye-doped polymer optical fiber luminescent solar concentrators: A comparison of the performance of step-index and graded-index fibers, *RP Cur. Tr. Appl. Sci.* **3** (2024) 51–55.

Original Research Article

Dye-doped polymer optical fiber luminescent solar concentrators – A comparison of the performance of step-index and graded-index fibers

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ARTICLE HISTORY
Received: 21 June 2024
Revised: 25 August 2024
Accepted: 27 August 2024
Published online: 30 August 2024

KEYWORDS
Dye-doped polymer optical fibers; :uminescent solar concentrator; Graded index fiber; Conversion efficiency.

ABSTRACT
Introduction of luminescent solar concentrators (LSC) help to improve the photovoltaic filed by reducing the cost of production and enhance the efficiency. An LSC contain a luminescent material embedded in a transparent waveguide so that they can absorb sunlight and re-emit and transport to the edges. These system can perform well without any light-tracking system and invariably under different lighting conditions. Here we analysed the performance of Rh640 perchlorate dye doped polymer optical fibers as an LSC. We compare the conversion efficiency of an uncladded step index (SI), cladded step index (CSI) and graded index (GI) fibers with four different diameters. All kind of fibers shows an enhancement in the efficiency with the fiber diameter. Also GI fibers shows better efficiency than other fibers. The performance of the fibers under different weather conditions were studied. It was found that fibers give better results under low pump powers.

1. Introduction

The conversion of sunlight into electrical energy using photovoltaic cells has been studied for more than 50 years [1–7]. Nonetheless, a few issues, such as the price of solar cells, restrict the productivity of solar energy. Additionally, a highly accurate sun-tracking system is required, increasing the device's cost. The introduction of luminescent solar concentrators (LSC) helps to improve the photovoltaic field by reducing the cost of production and enhancing efficiency [8]. An LSC contains a luminescent material embedded in a transparent waveguide so that it can absorb sunlight and re-emit and transport to the edges. These systems can perform well without any light-tracking system and invariably under different lighting conditions.

The development of fluorescence polymer-based optical fiber has received much attention in the field of optoelectronics and photonics fields for the past few years [9–11]. The ease of fabrication, low cost and flexibility of polymer optical fibers make them a perfect candidate for photonics and optoelectronics applications [12, 13]. The polymer host like PMMA will be compatible with different gain materials such as organic dye, rare earth materials and semiconductor quantum dots [14–16]. The active materials doped polymer optical fibers can perform as a luminescent solar concentrator (LSC) because they can absorb light from the sun through the surface, emit at a higher wavelength and guide the emitted light along its length to the end where the photovoltaic cell is attached [8, 12, 13].

Here we analysed the performance of Rh640 perchlorate doped polymer optical fibers as a luminescent solar concentrator. The effect of the diameter and the refractive index profile of the fiber were analysed. It was observed that graded index fibers perform better compared with the step-index fibers. Also, the diameter of the fiber and weather conditions play a crucial role in the conversion efficiency of the fibers as LSC. To the best of our knowledge, the LSC with dye-doped graded-index polymer optical fiber is reported for the first time.

2. Experiment

The polymer optical fibers were fabricated using a custom-made polymer optical fiber drawing tower. The luminescence solar concentrator (LSC) performance was analysed by exciting the fiber samples with a solar simulator. The fiber samples were placed perpendicular to the light source for the uniform side excitation as shown in Figure 1. The illuminated fiber length (Ze) was fixed as 4 cm. In the present study, we choose Rh640 perchlorate as the luminescent material because its emission coincides with the minimum attenuation region of PMMA as shown in Figure 2. Also, it is a high quantum yield organic dye with appreciable photostability. When the fiber sample is illuminated with solar light, the luminescent material embedded in the polymer matrix will absorb it and reemit radiation at a higher wavelength. Due to the waveguiding nature of the fibers, the emitted light will trapped and propagated along its length. The performance of the fiber as a luminescent solar concentrator (LSC) was analysed by measuring the conversion efficiency (η) and the concentration factor (C) [2, 19].

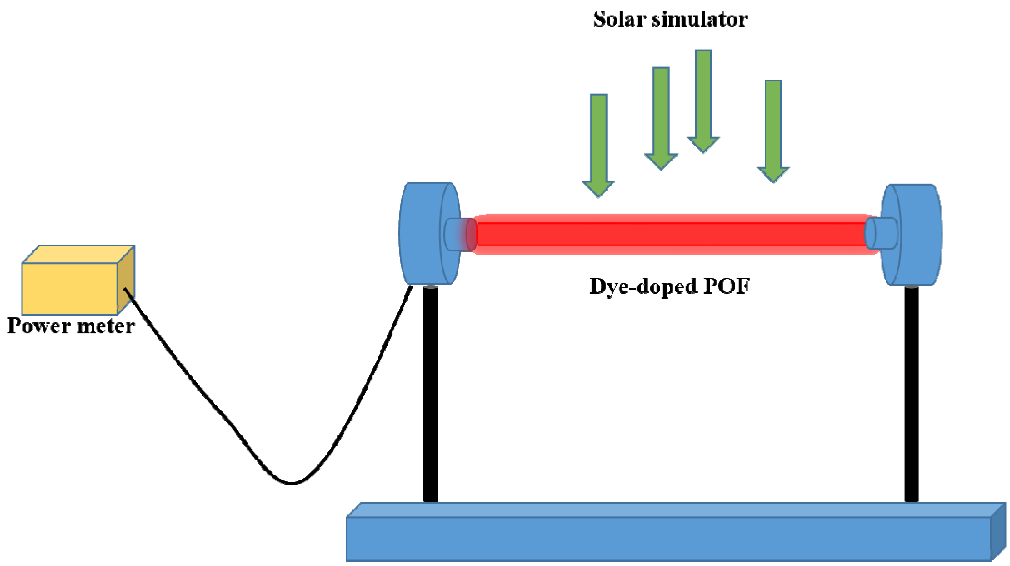

Figure 1: Schematic representation of the experiment setup.

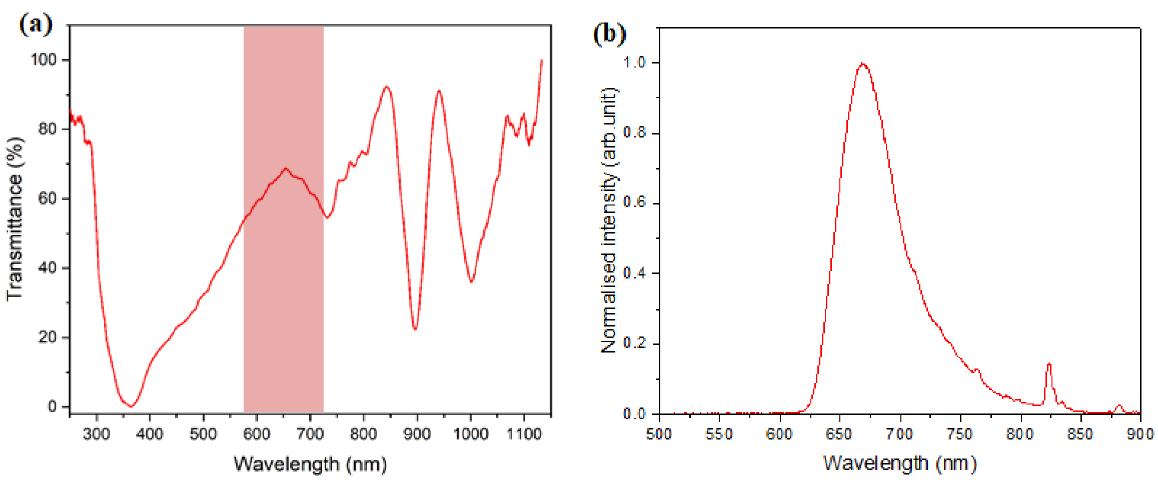

Figure 2: (a) Normalised transmission spectrum of PMMA;
(b) emission spectrum of Rh640 doped polymer fiber with the excitation of the solar simulator.

The efficiency (η) of an LSC can be defined as "the ratio of the radiative power emitted from the edge to the radiative power incident on the top surface".

$$\eta=\left(\frac{P_{out}}{P_{in}}\right)\times 100 \quad (1)$$

The radiative input power can be calculated using the equation

$$P_{in}=I_s D Z_e \quad (2)$$

where I_s is the intensity of the solar simulator, D is the diameter of the fiber and Z_e excitation fiber length.

The concentration factor is given by

$$C=\eta\times\frac{\text{Input surface area}}{\text{area of edges}} \quad (3)$$

3. Results and discussion

3.1 Determination of LSC parameters

Figure 3 illustrates the experimentally measured conversion efficiency of different fibers as a function of fiber diameter. The LSC efficiency increased with the fiber diameter, corresponding to the fiber's active volume. More light-matter interaction will take place in fibers with large diameters, which leads to the enhancement of the output power [2]. Also, for small fibers, the internal reflections take place along the length of the fibers, causing losses. From the figure, it is also clear that fiber with graded index fibers performs well compared with the step-index fiber. The refractive index gradient in the core region of the GI fiber helps to confine the light inside and propagate through its length. So the possibility of escaping the light through its surface is less than SI fibers leading to higher efficiency [20]. Table 1 summarises the experimental results.

Table 1: Calculated LSC parameters of the fiber samples

Diameter of the fiber (μm)	Input power ($\times10^{-3}$W)	Output power ($\times10^{-8}$W)	Efficiency ($\times10^{-3}$%)	Concentration factor
Un-cladded SI				
330	3.806	0.5866	0.154118	0.0238
400	4.614	1.3661	0.296114	0.0377
530	6.113	3.2355	0.529279	0.0509
630	7.266	9.4616	1.302106	0.1053
SI with cladding				
330	3.806	0.8799	0.231178	0.0357
400	4.614	1.9437	0.421316	0.0537
530	6.113	3.9921	0.653041	0.0628
630	7.266	12.3274	1.696494	0.1372
GI with cladding				
330	3.806	1.1982	0.314795	0.0486
400	4.614	2.3931	0.518696	0.0661
530	6.113	5.9559	0.974294	0.0937
630	7.266	13.6466	1.878038	0.1519

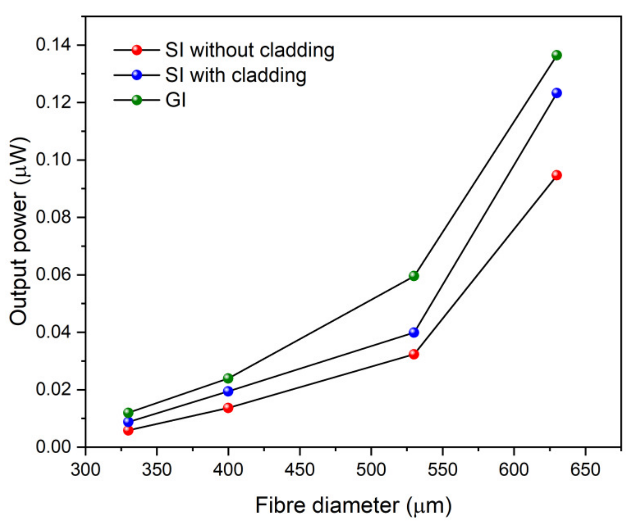

Figure 3: Variation of conversion efficiency with fiber diameter.

3.2 Effect of reflecting layer

The experiment was carried out for all fiber with a reflecting surface below the fiber sample. For all diameters, the efficiency is enhanced significantly in the presence of the reflecting surface as shown in Figure 4. The introduction of the reflecting surface improves the pumping efficiency by bouncing back the unabsorbed light from the solar simulator by the fibers [2, 19].

3.3 Effect of different weather conditions

The performance of the dye-doped polymer optical fiber solar concentrators under different weather conditions was analyzed by changing the intensity of the solar simulator using neutral density filters. Figure 5 shows the variation of the conversion efficiency with different input power. It is clear that the conversion efficiency decreases with increasing pump power. That is, the solar concentrators give higher efficiencies at lower pump power. This is because, at higher pump intensities, the possibility of photodegradation of the gain material is higher, which reduces the fiber's performance [2, 19].

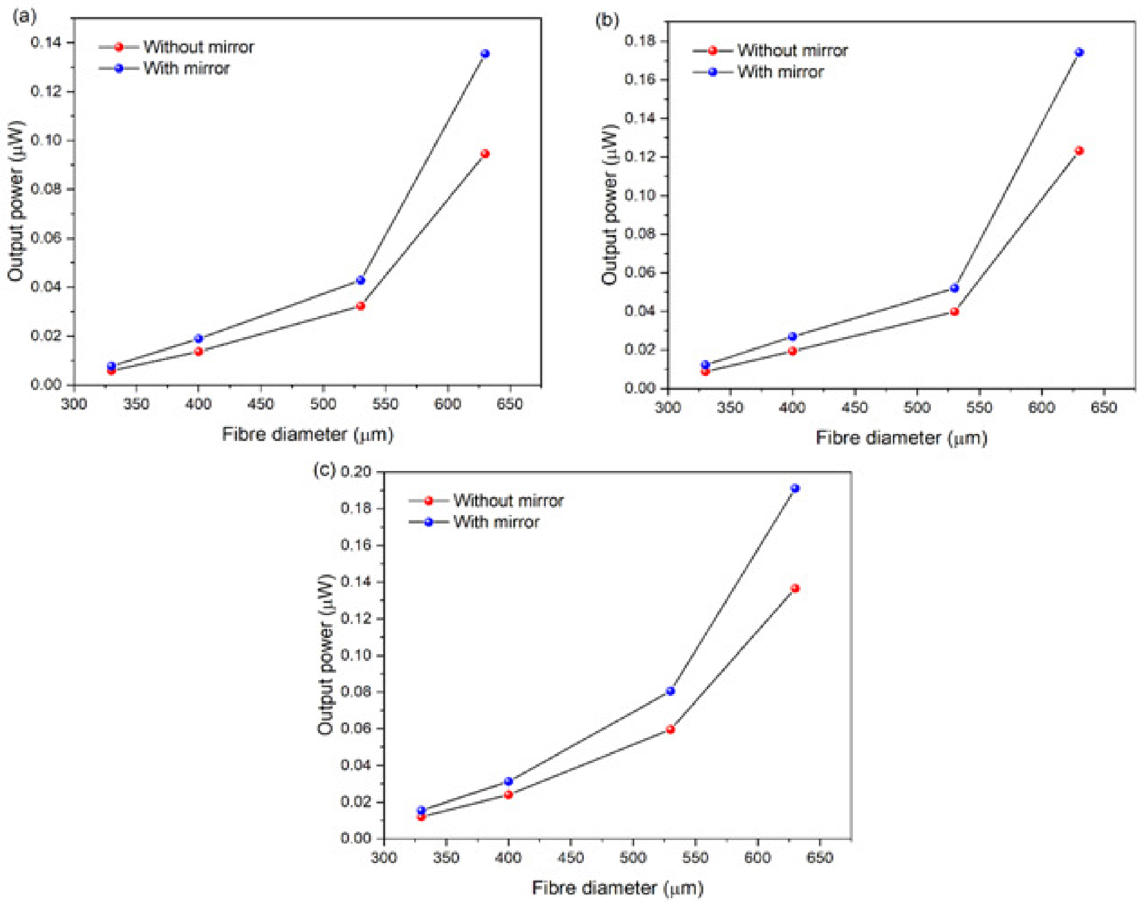

Figure 4: Variation of output power with reflecting surface for (a) fiber without cladding; (b) step index and (c) graded index fibers.

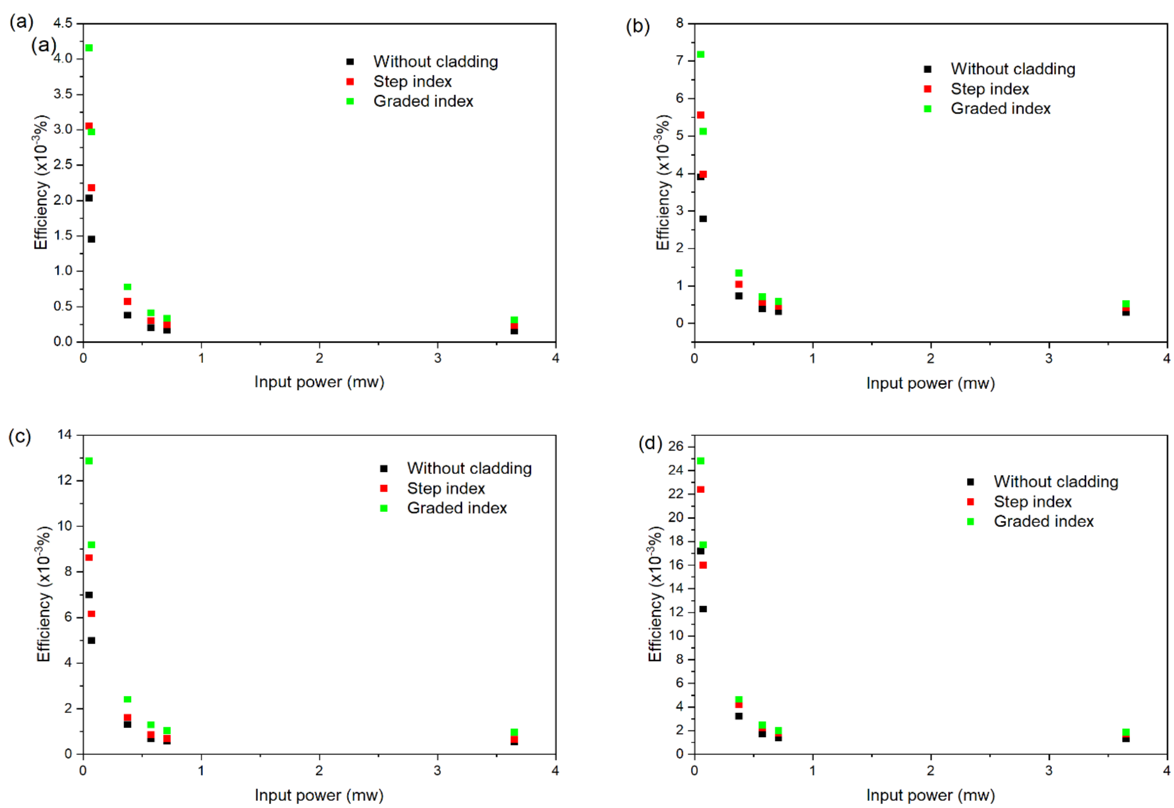

Figure 5: Variation of output efficiency with input intensity for fibers with diameter (a) 330μm; (b) 400μm; (c) 530μm; (d) 630μm.

4. Conclusions

We have analysed the performance of dye-doped polymer optical fibers as a luminescent solar concentrator. The conversion efficiency was found to increase with fiber diameter and graded index fibers show better performance in similar conditions compared with the step-index fiber. Also, the fibers show better performance under low pump powers and can work efficiently under different weather conditions.

Acknowledgements

The authors acknowledge DST-SERB (EMR/2016/003614 and EEQ/2018/000468), DST-FIST and CUSAT-USRF for the financial support. The authors would like to thank to Prof. Honey John, Inter University Centre for Nanostructures and Devices (IUCND), CUSAT for the solar simulator facility.

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