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High performance fluorescent fiber solar concentrators employing double-doped polymer optical fibers

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ABSTRACT

Novel double-doped polymer optical fibers have been fabricated by a bulk polymerization and fiber drawing process for fluorescent fiber solar concentration applications. Poly(methyl methacrylate) has been used as host material and a combination of organic dyes (Perylene/Lumogen Orange/Coumarin 1/Coumarin 6)) and metalorganic materials ($Eu(TTFA)_3Phen$) have been employed as dopants. A concise polymer analysis has been carried out, and the obtained fibers have been characterized under standard AM 1.5 G solar simulator excitation. The output power generated at one of the end surfaces of each of the fibers have been measured for 6 cm illuminated fiber length, obtaining a concentrated intensity of 0.31 mW/mm^2 and a fiber conversion efficiency of 0.41% in the best case. Besides, the performance of the fabricated fibers under different weather scenarios have been studied, showing good response at all the simulated day-conditions. Active fiber lengths of more than 6 m have been successfully tested, obtaining output intensities of 1.3 mW/mm^2. Good performance under constant excitation has also been reported during photostability experiments. The results obtained may have a strong impact in the field of luminescent solar concentrators as they offer a promising cost-effective route to green energy production.

1. Introduction

Due to the world's economic development, the needs and demands of the ever-growing population and environmental issues, such as the global warming, there has been an increasing interest in renewable energy sources in recent years. Photovoltaic (PV) technology appears to be a promising route to green energy production, as it is an abundant, clean and inexhaustible energy source. The goal of converting sun-light into electricity using PV cells has been subject of active research for more than sixty years, with the silicon-based solar cells dominating the field [1,2]. Considerable progress has been made in the PV field since then. However, the production of solar energy in a way that can compete economically with conventional energy sources remains hard to achieve due to two major drawbacks. On the one hand, the limited resources of silicon, together with the large areas of solar cells that are required, increase the cost of the system. On the other hand, to maintain the high conversion efficiencies of the solar cells, a very precise sun tracking system is needed, which also leads to a rise in the final cost of the system. A possible approach to reduce the expenses of the solar power harvesting system is the concentration of sunlight into a smaller area of solar cells by using less expensive optical devices (concentrators, mirrors and lenses) [3–6]. However, this kind of concentrators require a very accurate alignment of the optics, still need a sun tracking system, and they are not suitable for cloudy weather and diffuse light conditions, making these systems yet not competitive. In the 1970s the concept of luminescent solar concentrator (LSC) was first proposed by Weber and Lambe [7]. Many theoretical and experimental studies were carried out in early years since this first proposal, investigating different methods and materials [8–10]. However, LSCs were relegated to a period of inactivity due to the limits of that time materials, until more advanced ones were designed [11–14]. The LSC consist of a layer of transparent medium containing luminescent species which absorb part of the solar radiation and re-emit it in higher wavelengths, also known as energy down-shifting process. A fraction of the photons emitted by the luminescent material is trapped and transmitted by total internal reflection to the edges of the layer, where the PV cells can be attached

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for light-power to electricity conversion. LSC systems present multiple advantages, such as no need for tracking the sun, invariable performance under cloudy day and diffuse light conditions, and distributed heat dissipation over a large area. Besides, the use of cheaper transparent polymers as host materials, and the location of the PV cells at the edges of the active layer –requiring much smaller area of them–, decrease considerably the overall cost of the PV energy production. Nevertheless, the major drawback of the planar LSC lies in the limitation in coupling between the edge of the active layer and the PV cell and also the difficult wiring method for light transmission. Focusing on the aforementioned limitations, a new concept of cylindrical LSC based on doped polymer optical fibers (POFs), namely fluorescent fiber solar concentrator (FFSC), appears to be a competent solution. The cylindrical waveguide structure of the POFs adds several benefits. On the one hand, they are light-weight, thin and flexible, which permits an easy manipulation by the user. On the other hand, they can easily be attached to transparent optical fibers for light wave-guiding, which allows spatial separation between the light harvesting system and the final system placement when needed. Some theoretical studies have been carried out in the last years involving comparisons between cylindrical and planar LSCs [15–17]. In the research developed by K.R. McIntosh et al. it was found that the optical concentration of a cylindrical LSC is 1–1.9 times greater than an equivalent planar LSC, and the cylindrical LSC requires a smaller area of solar cells to produce the same amount of electricity as an equivalent square LSC [16]. It has also been found that for the proper functioning of a FFSC, the luminescent molecules must absorb and re-emit light very close to the surface. For this reason, clad-only doped fibers have started to be investigated [18,19]. Recently, a study on different fiber structures has been published targeting on the increase on the efficiency of the FFSC [20]. The optimum dopant material for FFSC applications must have broad absorption and emission bands, to ensure the use of as much of the solar radiation spectrum as possible. These bands should have very little overlap between them, as reabsorption events can be a considerable source of loss. Besides, the quantum yields of these materials should be high to avoid energy dissipation in different forms than radiation. As finding all the ideal properties in one material is not yet achievable, many different dopants have been studied for light concentration, such as, organic dyes [21–25], rare earth ions [26–28] and quantum dots [29–31].

In this work, we report for the first time to our knowledge, the fabrication of a solar concentration system that combines the benefits of the cylindrical structure of POFs with those of using a hybrid combination of dopants, mixing organic dyes and metal-organic materials. The broad absorption and emission bands of an organic dye permit a broad utilization of the solar spectrum, and the absence of overlap between absorption and emission spectra of metal-organic materials contribute to minimize the reabsorption losses. The fibers employed in this paper have been self-fabricated employing a double step process of bulk polymerization and fiber drawing, using poly(methyl methacrylate) (PMMA) as host material and a mixture of an organic dye (Perylene/Lumogen Orange/Coumarin 1/Coumarin 6)) and a metalorganic material ($Eu(TTFA)_3Phen$) as dopants. An analysis of the performance of these fibers have been carried out under solar simulator excitation. Promising results have been obtained in the field of PV technology.

2. Materials and methods

2.1. Experimental details

2.1.1. Chemical reagents and materials

All solvents, additives, and lauroylperoxide were obtained from Sigma Aldrich (St. Louis, MO, USA). 1-Butyl-mercaptan was purchased from Acros Organics (Morris Plains, NJ, USA). Solvents of HPLC quality, lauroylperoxide (97%) and butyl mercaptan (99%), were used without further purification. Technical grade solvents were distilled before use. MMA (> 99.8%) was obtained from Tokyo Chemical Industry Co., Ltd. (Tokyo, Japan) and distilled prior use. $Eu(TTFA)_3Phen$ was self-synthesized in our laboratory and precipitated in water; Perylene (> 99.5%) was purchased from Sigma Aldrich (St. Louis, MO, USA); Lumogen Orange (> 98%) was obtained from Tokyo Chemical Industry Co., Ltd. (Tokyo, Japan); Coumarin 1 and Coumarin 6 were purchased from Radiant Dyes Laseraccessoires GmbH (Wermelskirchen, Germany) and sublimated prior use. The optical fibers were coated with Efiron PC404F-AP (Luvantix, $n = 1.404$, 589 nm). The chemical structures of the dopants used in this work are shown in Fig. 1. $Eu(TTFA)_3Phen$ is characterized by its large separation between the absorption and emission bands (around 272 nm), its broad absorption band in the near ultra-violet (near-UV) region, and its narrow emission band at around 615 nm [32]. On the other hand, the selected organic dyes show both broad absorption and emission cross sections, long-term stability and high quantum efficiencies in PMMA [33,34]. These five dopants have a good solubility in MMA, which is a determining factor for the correct polymerization process. They further survive the rough polymerization conditions with long-term thermal stress at 100 °C in a radical initiated reaction. Moreover, the combination of the Eu(III)-chelate with a full organic dye, leads to small overlaps between the total absorption and emission bands. This fact, helps to reduce the losses caused by reabsorption processes, and therefore, to obtain high conversion efficiencies. Further information about the employed dopant combinations is gathered in Sections 3.1 and 3.2.

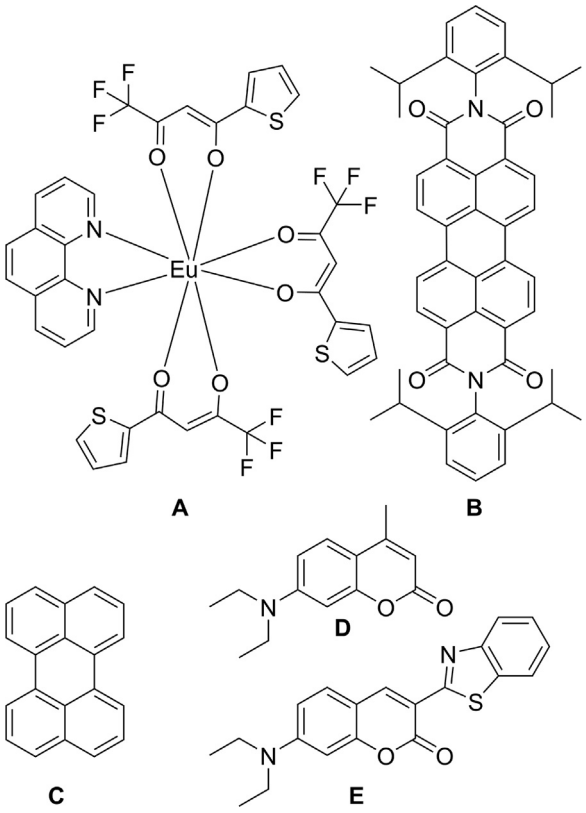

Fig. 1. Chemical structure of the dopants used in this study. A: $Eu(TTFA)_3Phen$; B: Lumogen Orange; C: Perylene; D: Coumarin-1; and E: Coumarin-6.

2.1.2. Preform polymerization and fiber fabrication

Various concentrations of two different dopants ($Eu(TTFA)_3Phen$, Perylene, Lumogen Orange, Coumarin 1 or Coumarin 6), lauroylperoxide (0.03 mol%) and 1-butyl-mercaptan (0.1 mol%) were solved in a nitrogen saturated MMA solution at room temperature. The monomer solution was filtered through 0.45 μm PTFE syringe filter (Chromafil,