Numerical Analysis of Doped Plastic Optical Fibers as Sunlight Collectors for Solar Cells

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***Abstract*—The model and numerical results presented are mainly intended for researchers who are nowadays trying to design efficient and inexpensive solar concentrators for solar cells by using plastic optical fibers doped with suitable dyes. One issue discussed in this work is the feasibility or not of lengthening the doped fiber in order to collect more light. Another one is the feasibility of increasing the dopant concentration with the aim of favoring the absorption of the impinging sunlight. We clarify both issues, and we discuss the most suitable type of dye, by calculating the achievable electric power in each case.**

I. Introduction

Some fluorescent molecules, such as coumarin-red, can not only absorb sunlight over a relatively broad range of wavelengths up to the red region, but also re-emit light at longer wavelengths, where the spectral responsivity of a typical silicon solar cell is greater. Furthermore, such molecules can be easily embedded in the core of a stretch of plastic optical fiber (POF) so that it will not only absorb part of the sunlight over its whole length, but also guide part of the re-emitted light to a solar cell [1]. If the type of dopant, the fiber length, and the dopant concentration are appropriate, the solar cell will deliver greater electric power than it would under direct exposition to the sun. Besides, POFs are inexpensive, and they do not need to be aligned towards the sun [2].

This work shows why certain dopants are better than others despite having a similarly broad absorption band, for example coumarine-red as compared to a mixture of rhodamines. It also shows and explains the existence of an optimum POF length and an optimum dye concentration, beyond which the obtained electric power could diminish drastically.

II. Modeling of the System

Figure 1 shows the spectral power distribution per nm of the sunlight impinging on a 1 mm solar cell (blue dotted line). The curve has been normalized to match the value of the sun irradiance on a sunny day at sea level (~ 900 μW/mm^2).

For the calculation of the power generated along the POF, which is illuminated by the sun perpendicularly to it, we consider the optical fiber as being composed of tiny cylindrical sections, each of which absorbs a fraction of the impinging sun power at each wavelength. The fraction absorbed depends on the average distance d_{ave} traveled by the sun rays through the cross section. Considering all refractions, d_{ave} has been numerically determined to be 1.838 times the fiber radius, We can calculate the fraction of sun power absorbed by each section as $1 - \exp(-\sigma^a(\lambda) \cdot (N-N_2(t,z)) \cdot d_{ave})$. In this expression, $\sigma^a(\lambda)$ is the absorption cross section of the dopant, and N and $N_2(t,z)$ are, respectively, the total and excited populations of dopant molecules per unit volume at each instant t and axial position z. The values of $N_2(t,z)$ are calculated by taking into account not only the sun energy absorbed in the perpendicular direction, but also the set of differential rate equations that describe the system in the axial direction [3]. These rate equations also serve to calculate the re-emitted power $P(t,z,\lambda)$. Finally, we calculate the power reaching the solar cell as the value of P at the end of the fiber ($z = L$) in steady state, i.e. when the elapsed time is large enough for the power to be constant (e.g. 300 ns).

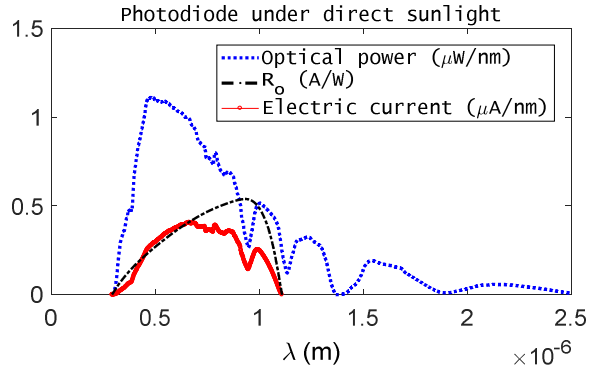

Fig. 1: Spectral distribution of the sun power impinging on a 1 mm solar cell at sea level on a sunny day, responsivity R_o of Si, and current generated.

For the calculation of the electric power, we can assume that the solar cell behaves as a current source of intensity I_{SC} proportional to the sum of the impinging optical powers at all wavelengths λ multiplied by the corresponding responsivities R_o of the solar cell (Fig. 1). When the load is the optimum one for maximum electric power, the voltage achieved under direct solar exposition in a sunny day is typically a few tenths of a volt (e.g. 0.5-0.6 V). The electric power for each value of P is calculated as the product of the open circuit voltage (~0.6 V), the fill factor (e.g. 0.8), and the corresponding value of I_{SC}.

The first dopant considered for the calculations is coumarin-red. Its emission and absorption cross sections,

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together with the attenuation of the material of the fiber (PMMA), are shown in Fig. 2 [4].

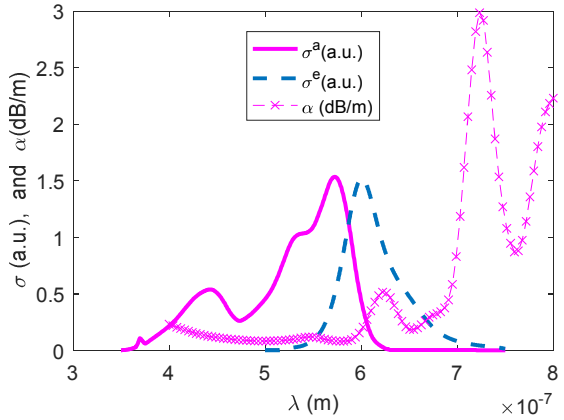

Fig. 2: Absorption and emission cross-sections of coumarin-red, and attenuation coefficients of a typical PMMA plastic optical fiber.

III. Results and Discussion

From a geometric point of view, the sun light absorbed by the doped POF is directly proportional to the fiber length L. However, part of this light may be unusable, because the attenuation in the axial direction of the re-emitted light can prevent photons generated sufficiently far away from the solar cell to reach it. Even in the hypothetical case in which the attenuation of the fiber material, namely PMMA, were reduced to a negligible value, there would be reabsorption by the dopant molecules, due to the overlap between the emission and absorption cross sections (see Fig. 2), so there would still be a maximum usable fiber length. These effects are illustrated in Fig. 3, which also shows that the electric power produced in the solar cell can be considerably larger than that obtainable under direct solar exposition, provided that the fiber is long enough.

Furthermore, a similar reasoning can be applied to explain other numerical results (not included here for space reasons) that show that coumarin-red is much better than a mixture of rhodamine B and rhodamine 6G. This is a consequence of a larger usable fiber length in the case of coumarine-red, because of a smaller absorption cross section of the dopant near the peak of the emission.

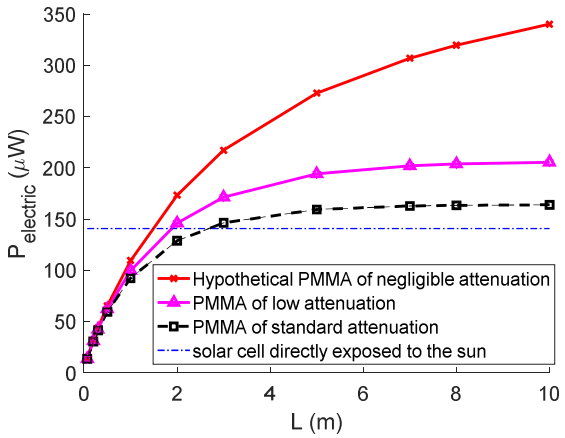

Fig. 3: Power supplied by a 1 mm solar cell, calculated for three types of PMMA POFs, and corresponding power under direct solar exposition.

For a certain fiber length, e.g. 5 m, one might think that increasing the dopant concentration (N) would serve to increase the fraction of impinging sun rays that are absorbed and, therefore, would be beneficial. However, Fig. 4 clearly shows that an increase of N from a typical value (e.g. $1.508 \cdot 10^{22}$) to a higher value N' could even be very detrimental to the achievable electric power. This effect can be explained by the reduction in the usable fiber lengths at all wavelengths when the concentration is increased, because the same reabsorption effects will occur in shorter distances, while stimulated emissions are almost negligible for any solar irradiance. Quenching effects are not taken into account here.

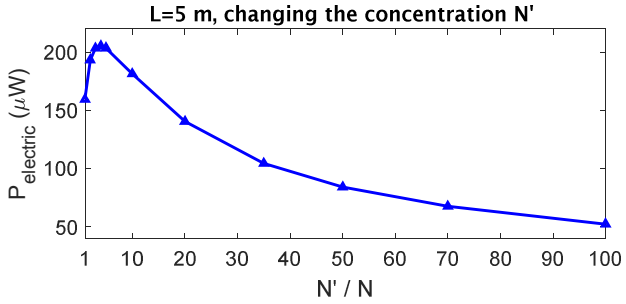

Fig. 4: Power supplied by a solar cell connected to a standard PMMA POF of 5 m if its concentration is changed from that of Fig.3 (N) to a higher one N'.

Conclusion

We model and characterize a system formed by a doped PMMA POF working as sunlight collector for a solar cell of the same diameter. The model takes into account the sun's spectral distribution, the absorption, emission and reabsorption phenomena, the attenuation coefficient of the PMMA, and the response of the solar cell. We show that increasing the dopant concentration is not always beneficial, and that the PMMA attenuation could also be highly influential. We also explain which types of dopants are better.

Acknowledgment

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