Light-harvesting through chaotic dissipative whispering gallery modes

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A key issue in the field of organic solar cells is to efficiently absorb sunlight within the very thin layers of active material (typically a few tens of nm). A new light-harvesting structure made of an array of interpenetrating glass cylinders is studied. The array is coated underneath with an organic solar cell. Experiments show a significant improvement of power conversion efficiency. This improvement is explained by discovering chaotic, dissipative whispering gallery modes inside the array. Finally, the production of optical entropy is computed and used to characterise the device performance.

Introduction

One way to reduce the cost of solar cells is to use amorphous Si or an organic material. However, due to the poor conduction in either of these, the resulting cells must be extremely thin. One is therefore faced with the challenge to optimally harvest sun photon within a very thin layer of active material. In practice, flat, thin-film solar cells fail to completely absorb the incoming light within the double passage afforded by the back metallic mirror. Exploiting interference effect by an appropriate choice of dielectric layers thicknesses within the cell has shown significant improvement [1]. However, this is not enough to obtain acceptable power conversion efficiencies and additional light-harvesting techniques remain necessary. One popular approach is to structure one or more interface within the cell to randomise the light field, after Yablonovitch's statistical ray theory [2]. However, the thickness of the active media considered here is well below one wavelength, in the case of organic photovoltaic, so that the hypothesis of ray optics is not satisfied. Moreover, to imprint a random embossing on a very thin cell is technically challenging. Indeed, mountains and valley must be of an amplitude at least comparable to the wavelength of light, which is presently large compared to the active layer thickness. Thus, there is a high risk of perforating the structure and to create internal short-circuits. This is why the alternative, easier to implement, solutions of covering the cell by a nearly randomizing structure [3] or by micro-lenses [4] have been considered. Another possibility is to exploit plasmon resonances [5] or diffractive elements but, by nature, these approaches cannot be broadband. Another interesting approach is to exploit resonances

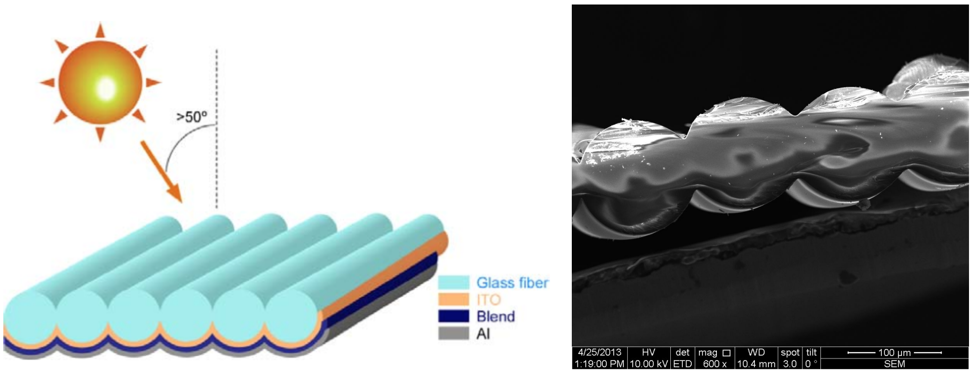

Figure 1: A Photonic Fiber Plate. Left: schematics. Right: SEM image.

in dielectric spheres [6, 7] or in dielectric shells [8]. The latter approach was tested experimentally, showing interesting prospect of light trapping, but no photovoltaic conversion was demonstrated.

Photonic Fiber Plate

In this work, we analyse a configuration proposed in [9], which consists of an array of silica fibres that are fused together, with their axes perpendicular to the ecliptic, see Fig. 1. Initial investigation was performed for fibre diameters ranging from 1 to 4 μm. Full-wave numerical simulations suggested that particular inclinations lead to the excitation of damped whispering gallery modes, giving rise to improved short circuit current at oblique incidence [9].

Encouraged by these early results, we have fabricated such structure by welding together an array of up to 10 commercial optical fibers. This array constitutes what we called a Photonic Fiber Plate (PFP). The degree of overlap between the cross sections of the fibers and the diameter of individual elements in the PFP can be varied by heating and stretching the fibers before welding. The result was that the fibre diameter was $\pm$ 72 μm and the array period was $\pm$68 μm, see Fig. 1. Moreover, we succeeded in fabricating a solar cell on one side of the array.

Results and analysis

One measure of performance of the cell is the External Quantum Efficiency (EQE), defined as the ratio of number of electric charges generated in the circuit to the number of photons incident on the device at a given wavelength. With the PFP, an EQE increase between 20% and 40% was experimentally demonstrated.

Given the diameter of the fibers, the limit of ray optics is clearly attained over the full visible range. A home-made numerical code was written in order to compute ray trajectories within the PFP. Ray tracing indicates that some of the rays that make up the incoming plane wave at a given frequency are trapped into whispering gallery modes. Other rays channel through the opening between adjacent cylinders, with a large probability of total internal reflection. The trajectories of such rays are chaotic but they also intermittently follow the circular boundaries of the array, in a way that is characteristic of classical

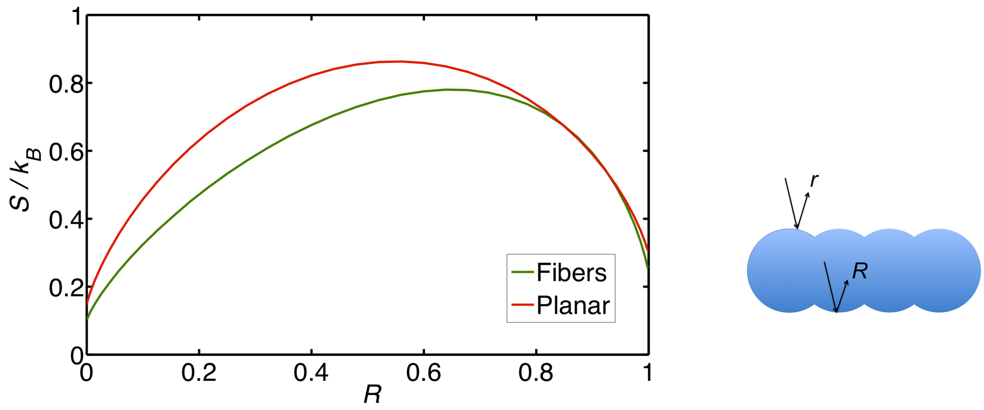

Figure 2: Calculated entropy production per photon as a function of the the intensity reflection coefficient R of the solar cell. $r \approx 4\%$ is the air/silica reflection coefficient.

whispering gallery modes. Moreover, these ray trajectories, together with secondary rays resulting from refraction/refraction can be associated to a statistical entropy S. According to the laws of reflection/refraction/absorption, a fraction of the photons incident on the PFP will be absorbed, the rest will be reemitted upwards in some direction. One can thus distinguish between the following states, after interaction with the PFP:

- state 0: the photon is absorbed by the cell,
- state 1: the photon exits the cell after 1^{st} contact with the top boundary,
- ...,
- state j: the photon exits the cell after j^{th} contact with the top boundary.

Each of the state above can be given a probability, which is computable by ray tracing. This set of probabilities can then be used, using Gibb's formula, to compute the scattering entropy S generated per photon after interaction with the PFP.

We computed the scattering entropy for a PFP assuming an air/silica reflection coefficient of 4% and using a variable reflection coefficient R at the bottom interface of the PFP. A small value of R means a large probability of absorption in the solar cell underneath the PFP. Conversely, a large value of R corresponds to a poorly absorbing solar cell. In practice, on may assume that a reasonable organic solar cell displays an intensity reflection coefficient $R \approx 0.3 - 0.5$. Indeed, if $R \approx 0$, there is no need to improve light harvesting while if $R \approx 1$, one cannot hope for a good efficiency in any way.

The result, displayed in Fig. 2, shows that in the region of interest, the entropy production is lower in the PFP than in a flat cell. This decrease in entropy production is directly related to an increase of absorption efficiency, as this reduces the uncertainty on the ultimate state of the photon.

Conclusion

In summary, we have experimentally and theoretically demonstrated a significant enhancement of light harvesting in a new kind of structure. This structure is new in the sense that it combines aspect of WGM and chaos in a way that improves light harvesting over a wide spectrum. The analysis of the light field in this Photonic Fiber Plate leads us to introduce a scattering entropy. The enhancement of absorption within the cell thanks to the PFP is associated to a decrease of production of entropy in the light field as a result of the interaction with the PFP, compared to a flat geometry.

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