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A Roadmap on Optics for Terawatt Scale Photovoltaics

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Abstract: The ongoing development of photovoltaics into terawatt scale poses a number of challenges where the optics and photonics communities can contribute. An international consortium recently compiled a roadmap that elaborates on these challenges.

1. Introduction

Decarbonizing the global energy system is one of the most pressing issues of our times. Several studies suggest that photovoltaic (PV) solar power and wind power will be the most important electricity generation technologies in a decarbonized energy system [1, 2]. Photovoltaics will enter the multi-terawatt scale in the coming years and "improved module efficiency will continue to be important to reduce both cost and space demands" [3]. Optics is crucial for further developing photovoltaics.

During the *Fourth European Workshop on Optics for Solar Energy* in October 2023 in Berlin, Germany, we decided on preparing a roadmap article on *Optics for Terawatt Photovoltaics*. The aim of this roadmap is to discuss the role of optics to enable photovoltaics on the terawatt scale, which is required to decarbonize the energy system. We present the most important scientific issues where we believe the optics community can contribute. As of April 2024, we are in the final phase of preparing the roadmap. With this contribution, we want to share the major insights of the roadmap with the attendees of the 2024 OPTICA Advanced Photonics Congress.

2. Summary of the Roadmap

We start the article with a summary of several important *optical concepts* that have been used in photovoltaics in the past: antireflective coatings as well as textured surfaces and/or interfaces are present in every high-end solar cell. While textures usually are random, also periodic textures have been investigated by many groups. It is paramount to reduce parasitic absorption. In concentrating photovoltaic systems direct sunlight is concentrated by factors in the range of several hundreds to a thousand, so that the amount of required energy intensive and costly semiconductor material for solar energy conversion is greatly reduced. Bifacial solar cells, which are becoming more and more prevalent, can utilize the light impinging on both sides of the solar cells, which increases the energy yield.

Photovoltaics is on the brink to *terawatt scale*. The pivotal chapter of the roadmap derives the topics to which the optics research community can actively contribute to facilitate such a large-scale exploitation. The chapter summarizes the different PV technologies ranging from crystalline silicon photovoltaics and thin-film solar cells to multi-junction solar cells. The following major challenges are identified: the time scale of the energy transformation, the sustainable production of PV, the integration of PV in the environment, increasing the power conversion efficiency (PCE) of PV modules and maximizing the energy yield of PV systems.

A high-quality solar cell is luminescent, hence light is generated in the solar cell because of radiative recombination. *Luminescence* of a solar cell gives us insight into both the electrical and optical properties.

Furthermore, internal luminescence can be exploited to increase the voltage in single-junction solar cells. In tandem solar cells, light generated in the top cell with the higher bandgap can be absorbed by the bottom cell with the lower bandgap and hence increases the generated current in the bottom cell. This effect is called *luminescent coupling*.

Because the global PV production is growing exponentially, using earth-abundant materials is of utmost importance. However, in state-of-the-art silicon solar modules large amounts of rare materials such as indium and silver are used. In the chapter *Ecodesign for solar cells by using earth-abundant optical materials*, we address the development of alternative optical materials based on earth-abundant elements.

Silicon solar cells have been dominating the PV market with a current share of more than 90%. Silicon technology is already so far developed that it reaches PCEs close to its physical limit of 29.4%. *Multi-junction solar cells* are regarded as the most promising concept to surpass the single-junction efficiency limit. The roadmap introduces the general multi-junction solar cell concept and discusses the specific optical challenges. Further, recent multi-junction solar cell technologies based on III–V semiconductors, silicon, CIGS and perovskites are summarized and specific scientific and technological questions are discussed.

While multi-junction solar cells are the most promising route to overcome the efficiency limitation of single-junction solar cells, *spectral shaping* aims to convert the solar spectrum into a spectrum that better matches to bandgap of the solar cell, which has a similar effect on the achievable efficiency. Broadly speaking there are three ways to convert the solar spectrum: downconversion of high-energy photons into a larger number of lower-energy photoexcitations; upconversion of below-bandgap photons into a (lower number) of above-bandgap photons and concentrating the sunlight at the expense of downconversion, often with luminescent solar concentrators. All categories increase the excitation density of a solar cell and thereby its power conversion efficiency.

Thin-film and photonic strategies can increase the front surface emissivity of the cover glass on the module, thereby allowing the module to take better advantage of *radiative cooling* to the sky and maintain a lower steady-state temperature. At the same time, significant reductions in heating can be achieved by *reflecting sub-bandgap photons* from penetrating into the module and causing parasitic heating. Optimizing both elements in a low-cost and scalable way represents an important opportunity for optics to improve thermal aspects of photovoltaic modules.

The performance of photovoltaic (PV) systems is assessed by a variety of key performance indicators such as levelized cost of electricity (LCOE), energy payback time, specific CO_2 emissions, or resource efficiency. All of these performance indicators require the total amount of energy harvested from the PV installation, taking into consideration seasonal and daily variations in irradiation conditions, spectrum, temperature, as well as all the details of the installation (e.g. module orientation, type of tracking, shadows, soiling, etc.). Therefore, accurately predicting the *energy yield* (EY) is pivotal for PV system and device architecture design of solar modules. The roadmap discusses two prominent examples that require detailed energy yield modelling: optimization of more complex multi-junction PV technologies (e.g. perovskite-silicon tandem PV) and bifacial PV. The PCE determined under standard testing conditions is not suitable to determine the optimal bandgap combination of perovskite-silicon tandem solar cells nor the perovskite layer thickness in bifacial perovskite-silicon tandem solar cells.

In building-integrated photovoltaics (BIPV) PV modules act as the building envelope and replace conventional materials for the facades. For social acceptance of BIPV, shape, texture and color are essential. Color, in particular, is critical. Discrete integration of PV is essential in heritage buildings; stakeholders in rural and urban areas prefer to harmonize the *aesthetic appearance of photovoltaic modules* with their surroundings. The final chapter of the roadmap summarizes the most commonly used coloring techniques in the production of BIPV modules.

3. Conclusion

The ongoing development of photovoltaics into terawatt scale poses a number of challenges where the optics and photonics communities can contribute. We presented a recently compiled roadmap that elaborates on these challenges. Amongst these are the consequent use of earth-abundant materials, increasing efficiency with multi-junction solar cells and spectral shaping, accurate energy-yield prediction and an appealing optical appearance.

4. References

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