Photovoltaic receivers for optical wireless power transfer and communication

Henning Helmers
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
henning.helmers@ise.fraunhofer.de

Abstract*: Optical power transmission uses special photovoltaic cells, also known as photonic power converters, to convert transmitted light into electricity. In optical communication, modulated light is used to transmit data. An elegant way to combine both technologies into a single optical link that is capable of transmitting data and power is to use the photovoltaic receiver device as simultaneous receiver for both power and data.*

1. Introduction

Optical power transmission and optical communication technologies have in common that photons are being transmitted from one place to another. On the one hand to transmit power, on the other to transmit information to the light receiving location. The light is either guided through optical fiber, known as power-over-fiber (POF) and fiber-optic communication, or transmitted through free space, known as optical wireless power transmission (OWPT) or laser power beaming and optical wireless communications (OWC). For the former, conversion of light to electrical power is done via a photovoltaic (PV) cell or module, typically using special photonic power converters (PPCs) which are optimized for monochromatic light conversion [1-3]. For communication, information is encoded in the amplitude using a modulation scheme of choice, e.g. orthogonal frequency division multiplexing (OFDM). Hence, at the receiver the data containing signal must be detected accurately in magnitude over time to enable decoding of the information. Typically PIN diodes or avalanche photo diodes (APDs) are used as detectors for this purpose, which are operated in reverse bias of tens (for PIN diodes) to hundreds (for APDs) of Volts.

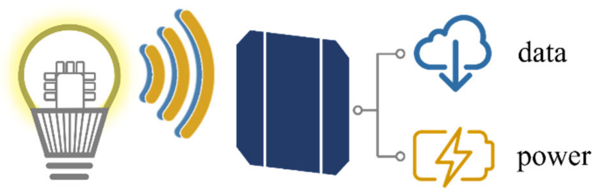

Fig. 1. A single photovoltaic cell can be used as combined receiver for both power and data.

Instead of two separate optical links for power and data transfer, both features can be integrated into a single link, which allows to reduce the number of parts and components, and is beneficial in terms of installation efforts and cost. A schematic of this combination, also known as simultaneous lightwave information and power transfer (SLIPT), is shown in Fig. 1. Using a single PPC as a receiver for the optical signal overcomes the need for reverse biasing and related power consumption. Instead, the receiver becomes self-sufficient or even power generating if operated in forward bias. Splitting the direct current (dc) part of the signal from the alternating current (ac) part allows to efficiently operate the PPC close to maximum power point while extracting data in a separate branch.

2. Photonic power converters

To realize photovoltaic cells with high conversion efficiency under monochromatic light conversion of a particular laser wavelength, the choice of absorber material is of highest importance. More precisely, fine-tuning the absorber material's bandgap E_g is the most relevant parameters. In practice, this fine-tuning can be done by using III-V compound semiconductors as absorbers and adjusting their exact composition. Fig. 2 shows a bubble chart of published PPC efficiencies from literature plotted against wavelengths. Efficiencies above 50% have been demonstrated for many relevant optical wavelength bands.

2.1 Multi-junction PPCs

The output voltage of a PPC is determined by the bandgap. Namely, with q being the elementary charge, the open circuit voltage V_{oc} can be expressed by E_g and the bandgap-voltage offset W_{oc}, which represents a useful metric for material quality or parasitic recombination: $V_{oc}=E_g/q- W_{oc}$. Increased output voltages can be achieved using multi-junction PPCs with series-connected subcells. An equivalent dc circuit of a multi-junction device is shown in Fig. 3a. Note that opposed to multi-junction solar cells where each subcell is made of a different material targeting different spectral bands of the broadband sunlight, multi-junction PPCs consist of stacked subcells all made of the same absorber material. Thus, their thicknesses must decrease from top to bottom, so that - despite the exponential Lambert-Beer law of absorption - all subcells generate the same current under monochromatic light illumination. The elevated output voltage comes with a division of the photo current, which can be advantageous in light of series resistance losses as well as to match the optimal load resistance for operation at maximum power point in practice. Besides these power related aspects, the series connection of subcells is also beneficial for the dynamic response of the device. A equivalent ac circuit is shown in Fig. 3b. Due to the inverse addition of capacitors in series, the series connection yields a reduced total device capacitance [4].

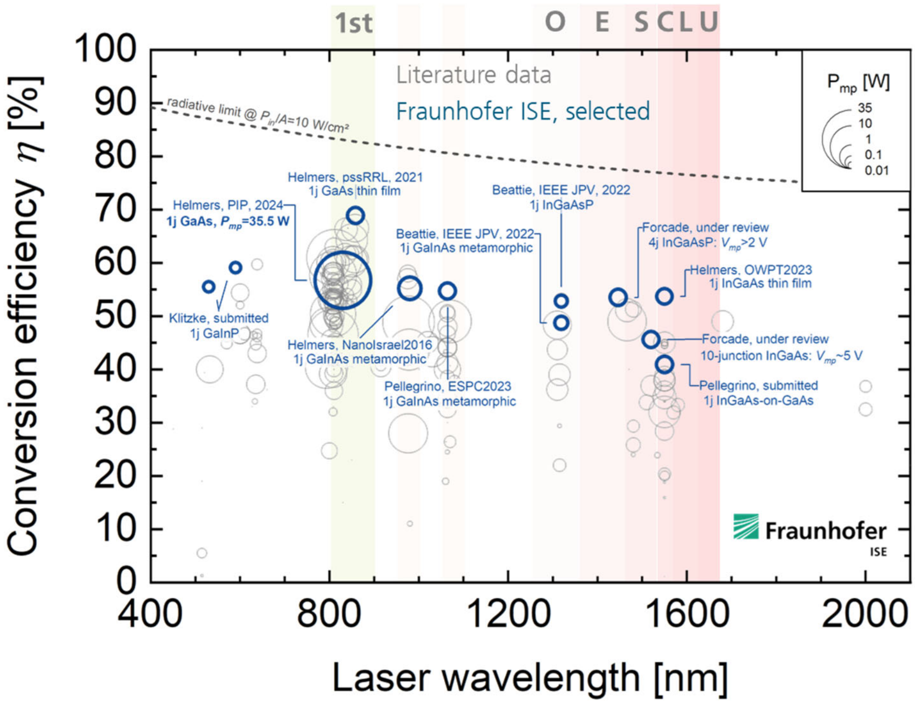

Fig. 2. Photovoltaic conversion efficiencies for monochromatic light conversion. The grey circles represent reported data from literature plotted against laser wavelength, where the size of the circle scales with the output power. The dashed line represents the fundamental theoretical limit (for an incident power density of 10 W/cm² and assuming the photon energy to equal the bandgap energy of the absorber and a quantum efficiency of unity). Efficiencies above 50% have been demonstrated for many relevant wavelengths bands. Selected results from Fraunhofer ISE are marked in blue from [1,5-12]. Plot updated from [13].

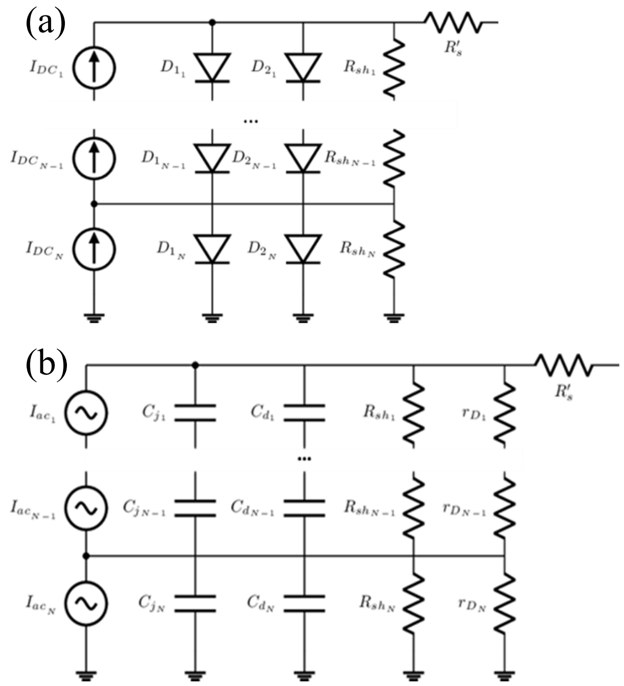

Fig. 3. Static dc (a) and dynamic ac (b) equivalent circuits of a multi-junction PPC. Each subcell is represented by a current source $I_{dc/ac,i}$, two diodes $D_{1,i}$ and $D_{2,i}$, junction and diffusion capacitances $C_{j,i}$ and $C_{d,I}$, parallel resistance $R_{sh,i}$, differential resistance $r_{D,i}$.

3. Conference presentation

We study the simultaneous optical power and data transfer using a photovoltaic receiver for both, ac signal and dc power. We study the use of a PPC with an ac-dc decoupled receiver circuit, consisting of an inductor branch with load resistance for dc power harvesting and a capacitor with a separate resistance for the ac communication signal. Relevant parameters of the PPC were studied analytically and compared with experimental measurements, namely the current-voltage characteristics and power conversion efficiency as well as capacitance-voltage dependence and differential resistance. Electrical circuit modeling of single- and multi-junction devices yielded insights into influences on the data transfer function. Theoretical and experimental findings are presented.

Acknowledgment
This work received funding through a Fraunhofer ICON grant “GreenCom”.

References

[1] Helmers, *et al*, phys stat solidi RRL 15(7), 2021.
[2] Algora, *et al*, Joule 6, 2022.
[3] Fafard, Masson, J Appl Phys 130, 2021.
[4] Pellegrino, *et al*, SPIE Photonics West 2025, SPIE 13359.
[5] Klitzke, *et al*, APL Photonics, 2025.
[6] Helmers, *et al*, Prog Photovolt Res Appl 32(9), 2024.
[7] Helmers, *et al*, NanoIsrael2016, Tel Aviv, Israel.
[8] Pellegrino, *et al*, Proc ESPC2023, Elche, Spain.
[9] Beattie, *et al*, IEEE J Photovolt 13(1), 2022.
[10] Helmers, *et al*, Tech Dig OWPT2023, Yokohama, Japan.
[11] Forcade, *et al*, Cell Rep Phys Sci, 2025.
[12] Pellegrino, *et al*, AIP Adv 15(2), 2025.
[13] Helmers, *et al*, SPIE Photonics West 2024, SPIE 12881.