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The effect of irradiance mismatch on a semi-dense array of triple-junction concentrator cells

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ABSTRACT

A method to determine the effect of cell-to-cell non-uniformity on CPV module performance is applied to a high-concentration photovoltaic system, comprising a linear semi-dense array of 5 series-connected 1 cm^2 triple-junction concentrator cells (lattice-matched GaInP/GaAs/Ge). Characteristic irradiance distributions were obtained by Monte Carlo ray-tracing of the concentrator optical system. Spatial apodizing filters were then produced such that, when illuminated with a spatially uniform radiation source, the desired irradiance distribution is obtained behind the filter. An equivalent circuit model of the array was developed and fitted against reference uniform irradiance measurements at concentrations ranging from 10x to 1678x. The fitted model was then validated vis-à-vis measurements under non-uniform irradiance imposed by the filters at concentrations from 99x to 494x. Both experimental and simulated results show a characteristic stepped I–V behavior associated with irradiance mismatch in series-connected arrays. Under the worst-case conditions of irradiance mismatch over the array, the efficiency drops to 28.5% as compared to 39% for the case of perfect uniformity. Due to the translational symmetry of the primary concentrator, a redesign of the module with parallel cell interconnects enables to mitigate the effects of irradiance mismatch. The methods provide an experimentally verifiable approach to determine the effect of irradiance mismatch on concentrator solar cell arrays without the need for prototyping of the concentrator optics. They may further be applied to determine the underlying characteristics and properties of cells and arrays subjected to nonuniform irradiation.

1. Introduction

The InPhoCUS project [1] aims to reduce the cost/m^2 of collecting aperture compared to other high-concentration photovoltaic (HCPV) systems by utilizing an inflated linear trough primary concentrator. The collector, shown schematically in Fig. 1, consists of a multilayer polymer mirror primary concentrator mounted on a rigid concrete frame, tracking on a *N-S* axis [2]. Each wing of the primary concentrates incident solar radiation to a focal plane where an array of reflective secondary concentrators, shown in Fig. 1(b), further concentrate the radiation onto the cell-receivers, coupled to the exit of each secondary concentrator. Since the primary concentrator tracks about a single-axis, a time dependent solar incidence angle, or skew angle, may exist between the incoming sunrays and the optical axis of the primary concentrator. For the given design, the skew angle may vary between $\theta_{skew}=-20^\circ$ and $+50^\circ$ under normal operating conditions. To maintain high-collection over the full range of skew angles, the secondary concentrators individually track on axes orthogonal to the primary tracking axis. The total geometric concentration of the system prototype is $C_g=580$x. The cell-receiver, detailed in Fig. 1 (c), consists of a linear (semi-dense) array of 5 series-connected 1 cm^2 concentrator cells. The 5-cell array is subsequently referred to as the *mini-module*. The cells are lattice-matched GaInP/GaAs/Ge triple-junction (3J) cells [3,4]. Each cell is connected in parallel with a high-current Schottky barrier rectifier (Vishay, model SS12P2L [5]), functioning as a bypass diode. The back contacts of the cells are vacuum reflow soldered to a direct bonded copper (DBC) board into which the electrical circuit is etched. The top contacts of the cells are wire bonded to the DBC board.

Many of the inherent difficulties of designing 2D dense arrays are mitigated by the linear semi-dense configuration. Circuitry and

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Nomenclature

Latin characters

$\langle E_{av} \rangle$	irradiance averaged over active area of module, x
A	area, cm^2
C_g	geometric concentration, x
DNI	direct normal irradiance, W/m^2
E	local irradiance, W/m^2
E_{av}	irradiance averaged over active area of cell, x = 1000 W/m^2
EQE	external quantum efficiency
f	objective function
FF	fill-factor
i	branch current, A
I	current through terminals of mini-module, A
j	cell number
J	current density, A/cm^2
k_B	Boltzmann constant, 1.38065×10^{-23} J/K
M	number of measurement points from SC to OC on the I–V curve
n	diode ideality factor, emission coefficient
N	number of cells in mini-module (5); number of different irradiance levels measured
P	DC power, W
q	elementary charge, 1.602176×10^{-19} C
R_s	series resistance, Ω
R_{sh}	shunt resistance, Ω
T	temperature, K
U	cell-to-cell uniformity
V	voltage across terminals of mini-module, V
v_F	forward bias voltage drop across bypass diode, V

Greek characters

ε_η	rms error between experimental and simulated efficiency
ε_{I-V}	rms error between experimental and simulated I–V curves
ε_{Voc}	rms error between experimental and simulated V_{OC}
η	efficiency
θ_{skew}	solar incidence (skew) angle, angle between normal vector of primary concentrator aperture and vector pointing to center of the solar disk
τ	transmittance

Abbreviations

3J	triple-junction
BD	bypass diode, also as subscript
D	diode in cell equivalent circuit model, also as subscript
DBC	direct bonded copper
DC	direct current
GS	grayscale (0 – black, 1 – white/transparent)
HCPV	high-concentration photovoltaics
MCRT	Monte Carlo ray-tracing
MPP	maximum power point, also as subscript
PAR	peak-to-average ratio
PVR	peak-to-valley ratio
rms	root-mean-square (error), also as subscript

Subscripts

0	reverse-saturation (current)
exp	experiment
j	pertaining to the jth cell or bypass diode
OC	open-circuit
ph	photogenerated (current)
post	post-filter (irradiance)
pre	pre-filter (irradiance)
SC	short-circuit
sim	simulation

electronics can be easily positioned on either side of the linear array, and cell-interconnects can be made without introducing significant gap losses. For the mini-module under investigation, there is a fixed inter-cell gap of 0.5 mm, yielding a ratio of active area to illumined area of 96.2% (3.8% gap loss). Using the same design and production method, the inter-cell gap could be potentially reduced to 0.35 mm (2.7% gap loss) or better.

A full-scale prototype of the HCPV collector was recently built and tested on-sun [6], and construction of a 200 kW demonstration plant in Biasca, Switzerland is scheduled to be completed in

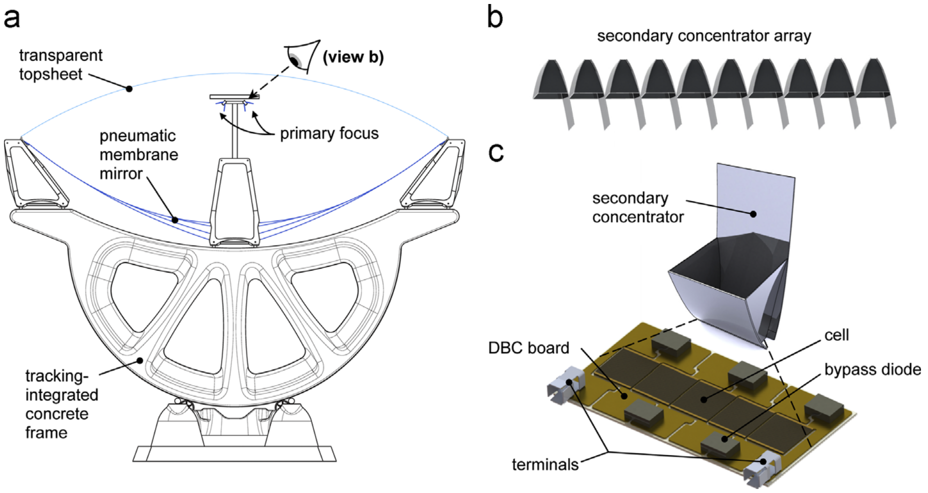

Fig. 1. Schematic of the InPhoCUS HCPV collector showing: (a) primary trough; (b) secondary concentrator array; and (c) detail of the 5-cell semi-dense array (mini-module).