Design and characterization of hybrid III–V concentrator photovoltaic–thermoelectric receivers under primary and secondary optical elements

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HIGHLIGHTS

- Novel integration of III:V concentrator photovoltaic cells-thermoelectric modules.
- Optimized thermoelectric module geometry for cell temperature sensing and cooling.
- New III:V triple-junction cell six-parameter one-diode equivalent model developed.
- The model fitted experimental current–voltage data with a low 4.44% mean error.
- High combined primary & secondary optical intensity gain coefficient 0.92 obtained.

ARTICLE INFO

ABSTRACT

Lattice-matched monolithic triple-junction Concentrator Photovoltaic cells (InGa$_{(0.495)}$P/GaIn$_{(0.012)}$As/Ge) were electrically and thermally interfaced to two Thermoelectric Peltier module designs. An electrical and thermal model of the hybrid receivers was modelled in COMSOL Multiphysics software v5.3 to optimize cell cooling whilst increasing photon energy conversion efficiency. The receivers were measured for current–voltage characteristics with the cell only (with sylguard encapsulant), under single secondary optical element at x2.5 optical concentration, and under Fresnel lens primary optical element concentration between x313 and x480. Measurements were taken in solar simulators at Cardiff and Jaén Universities, and on-sun with dual-axis tracking at Jaén University. The hybrid receivers were electrically, thermally and theoretically investigated. The electrical performance data for the cells under variable irradiance and cell temperature conditions were measured using the integrated thermoelectric module as both a temperature sensor and as a solid-state heat pump. The performance of six hybrid devices were evaluated within two 3-receiver strings under primary optical concentration with measured acceptance angles of 1.00° and 0.89°, similar to commercially sourced Concentrator Photovoltaic modules. A six-parameter one-diode equivalent electrical model was developed for the multi-junction cells under both primary and secondary optical concentration. This was applied to extract six model parameters with the experimental current–voltage curves of type A receiver at 1, 3 and 500 concentration ratios. Standard test conditions (1000 W/m^2, 25 °C and Air Mass 1.5 Global spectrum) were assumed based on trust-region-reflective least squares algorithm in MATLAB. The model fitted the experimental current–voltage curves satisfactorily with a mean error of 4.44%. The combined primary and secondary optical intensity gain coefficient is as high as 0.92, in comparison with 0.50–0.86 for crossed compound parabolic concentrators. The determined values of diode reverse saturation current, combined series resistance and shunt resistance were similar to those

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of monocrystalline PV cell/modules in our previous publications. The model may be applicable to performance prediction of multi-junction CPV cells in the future.

1. Introduction

Concentrator photovoltaic (CPV) technology utilizes low cost glass/polymer optics to significantly increase direct normal irradiance (DNI) photon flux onto a small [typically 5.5 mm × 5.5 mm] CPV cell. The optics concentrate sunlight and homogenise photon spectral distribution, significantly increasing cell efficiency. To maximize optical concentration two lenses are typically applied to CPV cells, a primary optical element (POE) and a secondary optical element (SOE). Modular CPV systems typically include dual-axis tracking systems to follow the sun's trajectory and maximize energy generation throughout the day.

CPV is a viable renewable energy technology for commercial-scale generation of solar electricity, with typically between x300 and x1000 optical concentration. The cumulative global installation capacity of CPV is currently greater than 370 MWp (December 2016) [1] with several power plants of ≥ 30 MWp capacity. These plants have been built in Golmud China, [Suncore, 60 MWp (2012) and 80 MWp (2013)], Touwsrivier, South Africa [Soitec, 44 MWp (2014)] and Alamosa, Colorado [Amonix, 30 MWp (2012)], with demonstrated reliability for over 7 years. For technical and economic viability annual DNI needs to exceed 2000 kWh/m^2, found in approximately 50% of global locations. A global map which represents the long-term average of daily/yearly global DNI is shown in Fig. 1 [2].

Compound semiconductor multi-junction CPV cells hold the highest world record cell efficiency at 46.0% [3], held by Fraunhofer ISE, Soitec and CEA-LETI [4]. CPV cells are structurally designed to minimize thermalisation and transmission losses. Multiple direct bandgap materials are epitaxially grown via metal organic vapour phase epitaxy (MOVPE) or molecular beam epitaxy (MBE). High purity III:V layers, with typical total epitaxial thickness of < 10 μm, have almost perfect crystallinity leading to low non-radiative losses in the CPV device. High extinction coefficients and anti-reflective coating of the cell enables effective absorption of incident solar photons in the wavelength range, 250–2500 nm. High charge carrier mobility and separation enables full-

spectrum energy harvesting. World III–V cell efficiency records have typically increased ~1% per year over the past decade. Advanced modelling indicates realistic cell efficiency targets of greater than 50% (1000x concentration) by 2020 [5]. High-volume production cell efficiencies generally closely follow research trends. Recent techno-economic evaluation states that to compete with crystalline Silicon system, CPV system efficiency needs to reach 40% with cell efficiencies of 50% and module efficiencies of 44% [6].

Previous literature on first-generation Silicon PV cell technologies list the positive benefits of hybrid photovoltaic-thermoelectric performance, increasing the annual electricity yield of the lone PV module by 11–14.7% at 25 °C [7]. There are only three research papers on III:V CPV cells integrated with thermoelectric (TE) technology. Two theoretical papers describe a GaAs/Ge PV-TE system providing a further 8% electrical efficiency relative to the lone PV technology [8]. Four PV technologies (compound Silicon, Copper Indium Gallium diselanide, Gallium Arsenide and a triple junction Gallium Indium Phosphide/Indium Gallium Arsenide/Germanium) were also theoretically modelled as part of a hybrid system [9]. For triple junction cell performance under 1-sun and higher concentrations, the hybrid device showed a larger system efficiency. One experimental reference paper detailed a hybrid III:V CPV-TE high system investigated under high optical concentration (approx. x200) [10]. The hybrid produced more power than the PV alone at concentrations larger than x100, using the thermoelectric module as a generator in Seebeck mode.

The original work in this paper investigates the functionality and performance of novel hybrid CPV-TE receivers. The thermoelectric module is used as both an accurate cell temperature sensor (via V_{oc}) and a heat pump in Peltier mode (upon application of current) for cell temperature control.

Domed-shaped single optical (SILO) lenses were used as the SOE for the receiver [11]. These optics also effectively encapsulate both the CPV cell and top electrical (n-type) contacts for protection against environmental conditions. The inevitable consequences of high irradiance
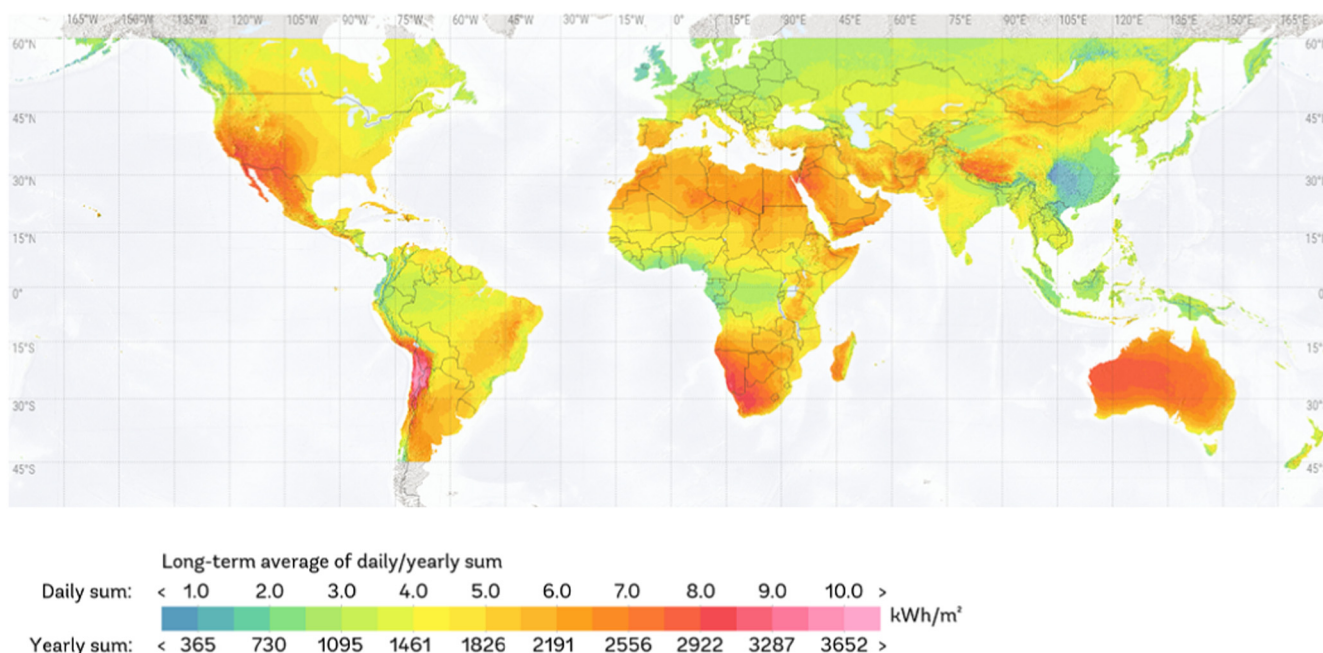

Fig. 1. Global resource map of direct normal irradiation. The solar resource is calculated by the Solargis model from atmospheric and satellite data with 10, 15 or 30-min time-steps. The effect of terrain are represented at a nominal spatial resolution of 250 m.

conditions are elevated cell temperatures and net power reduction. This is quantified by negative temperature coefficients for cell performance. The bandgap of each photon-absorbing layers is altered [12] reducing the cell voltage and slightly increasing photo-generated current at higher temperatures. Active solid-state cooling of the CPV cell increases the power output and potentially reduces thermal degradation of the III:V compound semiconductor cell. This becomes an important consideration when moving to higher optical concentrations to drive to lower levelised costs of energy.

A Closed Loop Integrated Cooler (CLIC) with temperature reference chip (Temp IC) was developed for additional temperature data in [13]. An AUTOLAB potentiostat system was also used for the I–V data acquisition in the experiments conducted inside a Faraday cage to eliminate any ambient light effects [14]. The POE was optimized using the Helios 3198 solar simulator at the University of Jaén [15]. A Delta Elektonika SM120-13 power supply unit was used to obtain the I–V measurements at the University of Jaen. A sensor based on the III–V material isotype solar was used to characterize the spectrum [16], and a solar spectral irradiance meter was applied to record the spectral direct normal irradiance under outdoor conditions for multi-junction cell based CPV modules [17].

Modelling multi-junction cell/modulus is another important task in design and characterization of CPV systems. For multi-junction PV cells/modules, there appears to be two methods for describing their I–V curves, i.e. (1) sub-cells model method, and (2) global model method. In the sub-cells model, the multi-junction cells/modules are divided into a few sub-cells, for example, for a triple-junction cell, its subcells include top-, middle- and bottom-cells connected in series by tunnel junctions. These three sub-cells have their own I–V curves to contribute the global I–V curve according to the Kirchoff's rules. Detailed I–V curves of a multi-junction PV cell/module show a variety in shape and pattern, depending on the cell/module design configuration and material properties, and usually can be determined by using a complex photon quantum calculation in terms of the terrestrial solar spectrum and cell geometry [18]. An analytical method for translating I–V curves of series-connected multi-junction solar cells was presented and the effects of irradiance, cell temperature and spectral variations were measured [19]. The complex photon quantum calculation was involved to estimate the electrical performance of multi-junction cells [20]. A theoretical analysis of the impact of atmospheric parameters on the spectral, electrical and thermal performance of a concentrating III–V triple-junction solar cell was carried out in [21].

In sub-cell models, once the short-circuit currents and open circuit voltages of the sub-cells are known, their 7 (two-diode model) [22], 8,

(a)

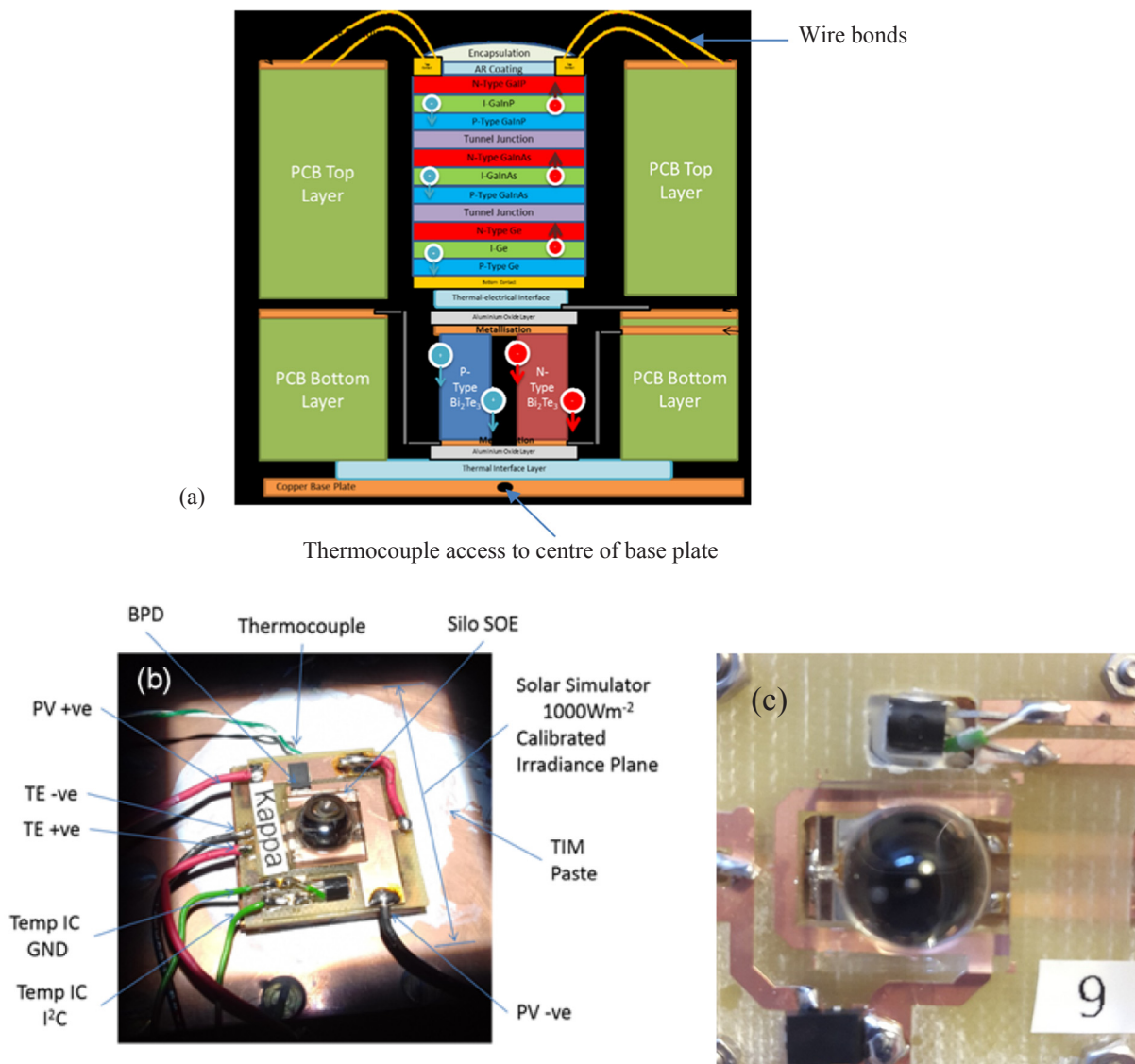Thermocouple access to centre of base plate

Fig. 2. (a) CPV-TE hybrid receiver PCB architecture [15] (b) Type A "Kappa" SOE-CPV-TE hybrid receiver overview (c) Type B SOE-CPV-TE receiver number 9.

[23], 10 (one-diode model) [22], or 24 [24] model parameters can be decided by making use of the measured global I–V curves [25]. In the global model, a multi-junction cell/module is no longer divided into a few sub-cells, instead is simplified to one equivalent electrical model [26] to reduce the number of model parameters in a great deal [27]. These model parameters can be decided by experimental global I–V curves.

In the paper, the novel hybrid receivers were designed, but also electrically and thermally measured under different cell temperature conditions. Standard test conditions (STC) of 1000 W/m^2 irradiance, 25 °C temperature and AM1.5G/D spectrum conditions gave baseline cell performance data. The experimental I–V curves of type A receivers at 1, 3 and 500 concentration ratios were represented by making a proposed six-parameter equivalent single-diode electrical model. The six model parameters were extracted from the curves based on the trust-region-reflective least squares algorithm in MATLAB. The determined parameters were contrasted with those of the monocrystalline PV cell/modules with crossed compound parabolic concentrators (CCPC) in existing papers.

From the modelling context, the paper further exhibits the novelty of the proposed six-parameter single-diode equivalent electrical model for the multi-junction PV cells/modules, particularly, the power function for the optical gain of a multi-junction cell with SOE only, or with both SOE and POE at a geometrical concentration ratio (CR) as high as 500.

2. Experimental

The hybrid receivers were manufactured using standard cleanroom and wire-bonding techniques. The architecture of the hybrid device shown in Fig. 2(a) [12] includes two active components. A 5.5 × 5.5 mm lattice-matched triple junction solar cell. These cells were bonded to a pre-metallised Marlow CM23-1.9 bismuth telluride TE module, in receiver type A, see schematic Fig. 2(b) "Kappa". The hybrid CPV cell-thermoelectric module hybrid receiver was modelled and re-designed for operation at x300 concentration. Modules were supplied by European Thermodynamics for receiver types B and C. The primary aim was to keep the cell temperature below the manufacturer's high temperature limit of 85 °C. The thermal contact between the CPV cell and the TE module was improved by changing the thermal interface material and by reducing its thickness for receiver types B and C. The CPV cells used in the hybrid receivers were from the same

manufacturer, but from three different wafers/growth campaigns. A photograph of receiver type C, with improved PCB design to reduce the likelihood of hot-spot formation, is presented as Fig. 2(c). A water heat exchanger and appropriate thermal interface material (TIM) was used in all indoor solar simulator experiments. Temperature measurements were taken at the TE cold-side and ambient temperature using a K-type thermocouple, in conjunction with a Fluke 52II thermometer. A Closed Loop Integrated Cooler (CLIC) and temperature reference chip (Temp IC) were used for additional temperature data as reported in previous work [13]. A forward looking infrared camera (FLiR i7) was used for thermal imaging distribution measurements.

At Cardiff University a LCS-100 Class ABB (ASTM, IEC and JIS standards) solar simulator, with the 1000 W/m^2 calibrated irradiance plane found using a Kipp and Zohan CMP11 pyranometer, was used for STC current-voltage (I–V) scans. An AUTOLAB potentiostat system was used for I–V data acquisition, and the experiments were conducted inside a Faraday cage to eliminate any ambient light effects [14]. Steady-state temperatures of 25 ± 1 °C were achieved, prior to measuring CPV cell I–V curves. This was to minimize electrical output changes due to the temperature coefficients of the cell. The current-voltage graphs for type B receivers are presented in Fig. 3. Measurement uncertainties for the experimental equipment used are presented in Table 1 and CPV cell and CPV-TE module characterization data are given in Table 2.

The SOE CPV-TE hybrid receivers [14] were connected in two series-connected strings of three receivers, matched via maximum power point current (I_{mpp}) values. The primary optical elements, designed to give x313 concentration ratio, were added to the module. To protect the connecting wires and temperature sensitive devices on the hybrid receivers, off-axis shield was added to reflect back solar irradiation using 3M Reflectec film. High-temperature kapstan tape was used to secure the film.

The vertical distance of the POE was optimized using the Helios 3198 solar simulator from Solar Added Value Company at the CEAEMA in the University of Jaén [15]. A Delta Elektonika SM120-13 power supply unit was used to obtain the I–V measurements at the University of Jaen. This solar simulator uses a Xenon flash lamp for simulating the solar radiation and a parabolic mirror as a collimator. The spectral irradiance distribution can be tuned to match the AM1.5D reference spectrum by using appropriate filters, and the collimation angle is around ± 0.3°. Also, the Spectra Matching Ratio (SMR) for the top and middle sub-cells was monitored through the measurements of
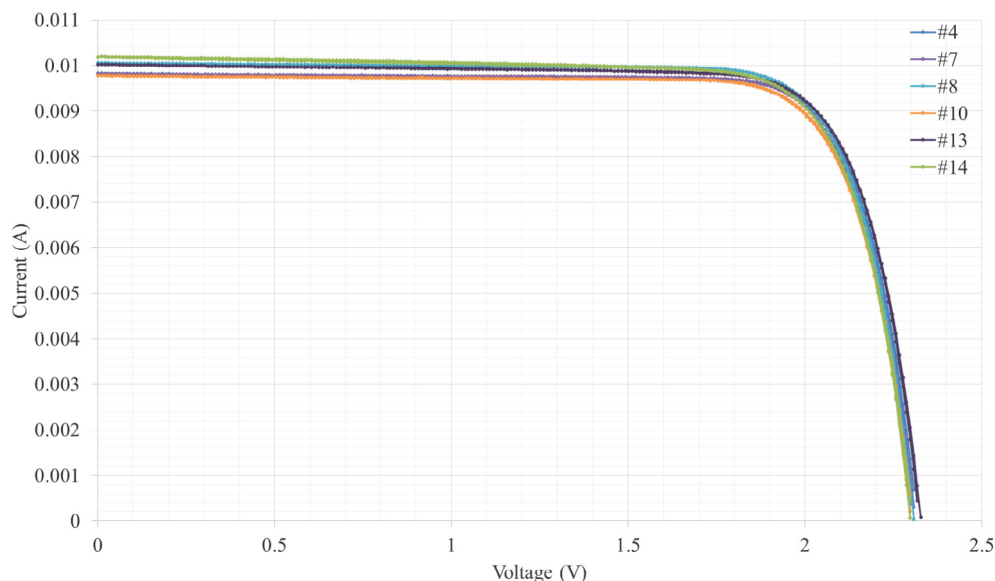

Fig. 3. Current-Voltage curves for type B receivers.

Table 1
Equipment measurement uncertainties.

Equipment	Resolution	Interval	Range of reading	Uncertainty	Other
Autolab	I 6E−6 A	3E−7 A	± 2A	Accuracy ± 0.2%	
	V 0.3E−6 V	0.15E−6 V	± 10 V		
Pyranometer	A 5.12 µV/W/m^{-2}			Temperature change < 1%	Range −40 to 80 °C
(Kipp & Zonen	A 8.89 µV/W/m^{-2}	2.56 µV/W/m^{-2}	285–2800 nm	Time change < 5 s	4000 W/m^2 max
CMP11)	A 9.01 µV/W/m^{-2}				
Spectroradiometer	1 nm	0.5 nm	24–800 nm	± 2 °C stability	Range −10 to 40 °C
Silicon reference					
Cell seaward solar survey 100)	1 Wm^{-2}	0.5 Wm^{-2}	100–1250 Wm^{-2}		1 °C ± 0.5 °C resolution
FLiR i7 camera	0.1 °C	0.05 °C	Range −20 to 250 °C		9 Hz, 75–13 µm detection
IR thermometer	3 °C	1.5 °C	Range −25 to 265 °C		Area 0.08 m^2 @ 0.6 m
(Maplin TN439L0)					Distance 0.13 m^2 @ 1 m
Thermocouples (K type, PTFE 1 m)	3 °C	1.5 °C	Range −75 to 250 °C		
Thermocouples reader (Fluke 52)	0.1 °C	0.05 °C	0–9999 °C		Thermocouple dependant
Multimeter	V 0.01 mV	0.005 mV	0–1000 V		
(Chauvin Arnoux)	0.1 Ohms	0.05 Ohms	0–60 MOhms		

component cells to ensure the adequate input spectrum. This type of light source has a small time period for each measurement (< 2 ms). It is effective for large area testing, without need for a continuous light source or temperature control of the receiver. The configuration of SOE-CPV-TE receivers is given in Fig. 4(b).

The samples were located using a right-angle clamp from Thor labs, then the focal length distance was adjusted until the light spot of the POE was incident on the fulcrum of the SOE. When locating the samples within the clamp, type B receivers were more compatible in size than type A. This had the potential to introduce rotational inaccuracies for the type A receivers. This POE alignment procedure introduced a systematic error between the obtained I–V traces. However, the data obtained was comparable to experiments using the type B receivers both outdoors in the module, under POE, and indoors as receivers under SOE only.

After optical alignment, the acceptance angle of each string was

Table 2
CPV-TE hybrid receiver pre-manufacture cell and thermoelectric device data.

Receiver			Wafer	Cell	Themoelectric module			
ID	Type	Optics	ID	ID	Batch	ID	RAC (Ohms)	Thick (mm)
Kappa	A	SOE	#0556	48	CM23-1.9		1.23	1.63 + metallization
Lambda	A	No	#0556	40	CM23-1.9			
4	B	SOE	#2047	74	2,484,935	4	1.98	2.360
7	B	SOE	#2047	48	2,484,935	7	1.93	2.410
8	B	SOE	#2047	67	2,484,935	8	2.08	2.400
10	B	SOE	#2047	47	2,484,935	10	1.99	2.410
13	B	SOE	#2047	93	2,484,935	13	1.99	2.510
14	B	SOE	#2047	119	2,484,935	14	1.89	2.480
21	C	No	#4853	49	2,484,935	21	1.95	2.362
22	C	No	#4853	61	2,484,935	22	1.97	2.422
23	C	No	#4853	26	2,484,935	23	1.88	2.484
24	C	No	#4853	39	2,484,935	24	1.88	2.553
25	C	No	#4853	27	2,484,935	25	1.96	2.485
26	C	No	#4853	80	2,484,935	26	1.98	2.544
30	C	SOE	#4853	36	2,484,935	30	2.02	2.474

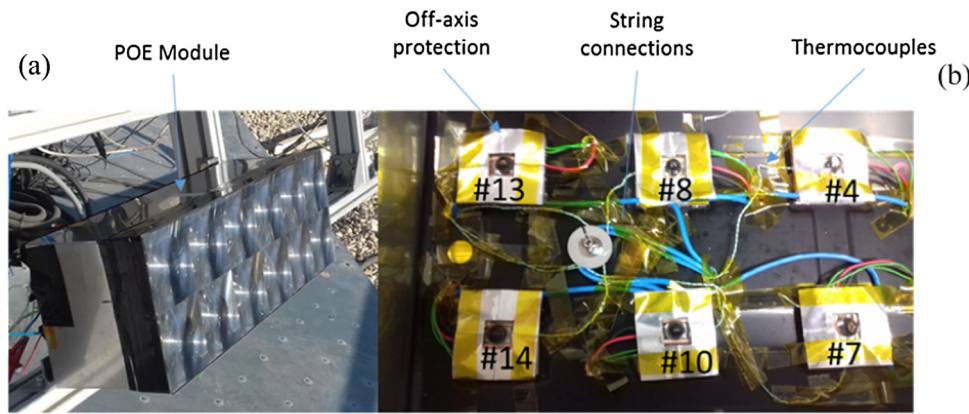| Receiver	1-sun data					330-sun data				
ID	I_{sc} (mA)	V_{oc} (V)	P_m (mW)	FF (%)	η_{eff} (%)	I_{sc} (A)	V_{oc} (V)	P_m (W)	FF (%)	η_{eff} (%)
Kappa	4.47	2.26	8.30	82.2	27.4	1.528	2.7994	3.496	81.7	33.8
Lambda	4.44	2.28	8.59	84.9	28.4	1.521	2.8203	3.502	81.6	33.8
Mean	4.46	2.27	8.45	83.6	27.9	1.524	2.81	3.499	81.65	33.8
4	4.50	2.19	7.62	77.4	25.2	1.474	2.81	3.402	82.3	34.3
7	4.50	2.16	7.65	78.7	25.3	1.469	2.79	3.334	81.4	33.8
8	4.52	2.19	7.71	78.0	25.5	1.473	2.79	3.379	82.2	34.3
10	4.52	2.16	7.54	77.2	24.9	1.479	2.80	3.374	81.4	34.1
13	4.48	2.19	7.72	78.6	25.5	1.462	2.81	3.373	81.9	34.2
14	4.48	2.17	7.66	78.6	25.3	1.458	2.79	3.311	81.4	33.6
Mean	4.50	2.18	7.65	78.1	25.3	1.469	2.80	3.362	81.77	34.05
21	4.14	2.49	8.76	85.0	28.9	1.384	2.86	3.368	85.2	33.3
22	4.15	2.49	8.60	83.4	28.4	1.379	2.86	3.348	84.7	33.3
23	4.13	2.49	8.55	83.2	28.3	1.390	2.85	3.364	84.8	33.1
24	4.14	2.49	8.53	82.7	28.2	1.384	2.85	3.351	84.9	33.1
25	4.13	2.50	8.68	84.1	28.7	1.389	2.86	3.379	85.2	33.2
26	4.14	2.49	8.75	84.9	28.9	1.379	2.87	3.353	84.6	33.3
30	4.12	2.51	8.75	84.5	28.9	1.388	2.85	3.373	85.3	33.1
Mean	4.14	2.49	8.66	84.0	28.6	1.385	2.86	3.362	85.0	33.2

Fig. 4. CPV-TE module on-sun (a) and overview of the SOE-CPV-TE receivers (b) at Jaén University.

measured with the Helios 3198 CPV solar simulator at the CEAEMA in the University of Jaen as a quadrant of the module. Q1 for receivers #13 and #8 and Q4 for receivers #10 and #7. STC conditions were used, $1000 \, W/m^2$, spectral irradiance similar to AM1.5D reference spectrum, SMR (top/mid) = 1 ± 0.05 and room temperature of $25 \, °C \pm 0.5 \, °C$. The optimum alignment was considered at the point 0 of the x-axis. The values obtained were 1.00° (string A, 13, 8 & 4) and 0.89° (string B, 14, 10 & 7), given in Fig. 5. The results are comparable to most commercial modules.

The module was mounted on a high-precision dual-axis tracker from BSQ Company located on the rooftop of the CEAEMA, with a known mis-alignment of within 0.2° accuracy, is shown in Fig. 4(a) [15]. The measurement setup at CEAEMA, Jaén University, included an atmospheric station MTD 3000 from Geonica Company to record the main atmospheric parameters. This station incorporates a pyrheliometer and various pyranometers to measure different components of the irradiance (i.e. global horizontal and normal, direct normal and diffuse horizontal). It also includes several sensors to record other crucial parameters such as air temperature, wind speed and direction or relative humidity Also, the centre is equipped with a sensor based on III–V material isotype solar cells from Black Photon Company to characterize the spectrum and a solar spectral irradiance meter (SolarSIM-D2) from Spectrafy Inc. to record the spectral direct normal irradiance among other key parameters for the outdoor spectral characterization of multi-junction based CPV modules such as aerosol optical depth at 550 nm (AOD550) [16] or precipitable water (PW) [17]. An IV tracer was used to evaluate CPV cell performance of all three receivers within each string. The rear substrate temperature for all of the receivers were recorded during I–V scans using thermocouples and two Picologger TC-08s. Three power supplies were used to supply the excitation current to the TEM during testing. A schematic of the setup is given in Fig. 6.

Type C receivers 21, 22, 23, 24, 25, 26, detailed in Table 2, were manufactured for I–V and accelerated lifetime testing. Receiver 30 had a SILO SOE attached to the cell with Sylguard encapsulant. The optical concentration of the SOE was calculated with respect to I_{sc} as x2.57. The data is presented as Fig. 7. Comparative measurements were performed on type A "Kappa" and type B receiver #13 under SOE at Cardiff University and SOE + POE at Jaén University, see Fig. 8. Under 1-sun conditions, measured under SOE, the V_{oc} of "Kappa" was 0.1 V higher than that of receiver #13, indicating ~25–30 °C lower cell temperature for Kappa. The I_{sc} of #13 was 0.02 A higher than Kappa when measured under POE, consistent with a lower cell temperature for Kappa.

The current–voltage characteristics of type B hybrid receivers were measured under primary optical concentration in the solar simulator at CEAEMA, the results are presented as Fig. 9 and Table 3. In comparison with CPV cell probe measurements, based on the I_{sc} data, the concentration ratio under the POE optics was x371 for Kappa (type A) and x375 for receiver #13 (type B).

The type B CPV-TE hybrid receiver #9 was measured for current–voltage characteristics with a temperature range of 5–80 °C. The TE module was used to accurately measure and control operational CPV cell temperature and the I–V results are presented in Fig. 10(a). The decrease in V_{oc} and V_{mpp} with temperature increase is highly linear (R^2 0.983 & 0.972), see Fig. 10(b). The temperature coefficients are −0.00255 and −0.00221 V/K. The increase in I_{sc} and I_{mpp} with temperature increase is linear (R^2 0.754 & 0.880), see Fig. 10(c). The temperature coefficients are 0.00049 and 0.00048 A/K. The temperature coefficient for CPV cell efficiency was calculated as −0.055%/K. The trend was highly linear (R^2 0.957) over the 75 °C temperature range tested, see Fig. 10(d).
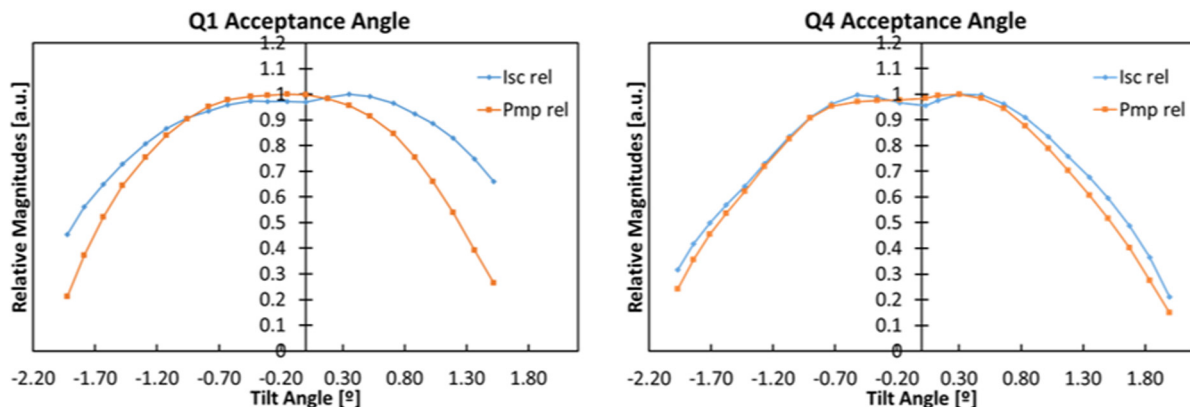

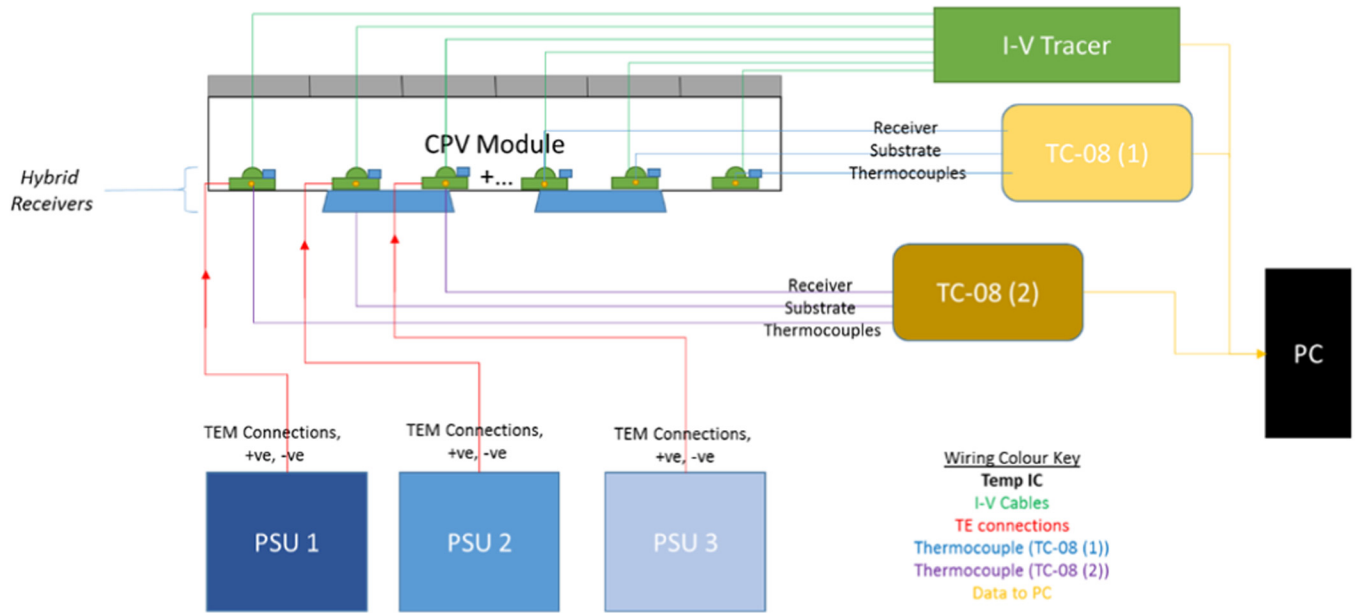**Fig. 5.** Acceptance angle data for quadrants 1 and 4 of the type B CPV-TE hybrid module.

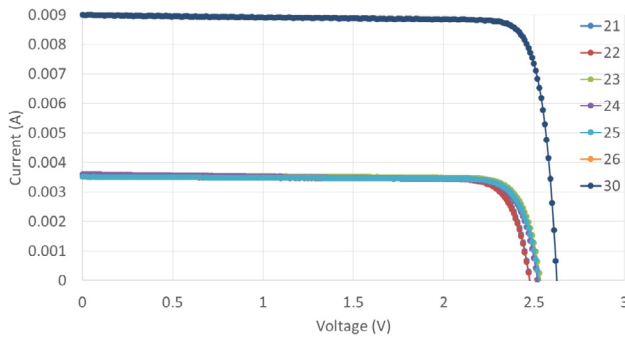**Fig. 6.** Metrology of the on-sun POE-SOE-CPV-TE receiver module at Jaén University.

Fig. 7. Type C receiver I–V plots without SOE (21–26) and with SOE optics (30) for accelerated lifetime testing.
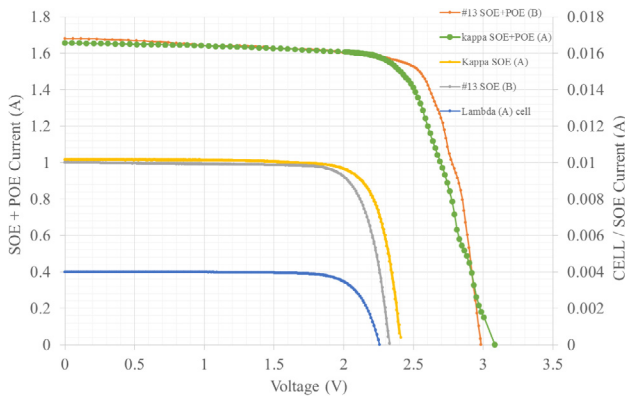

Fig. 8. I–V data for type A "Lambda" and "Kappa" and type B "13" receivers.

3. Thermoelectric cooler model

An electrical and thermal model of the thermoelectric module, linked to a thermal model of the PV cell was produced in the finite element analysis program COMSOL Multiphysics 5.3. The thermal impact of the SOE was not included as much of the initial fitting was performed without the SOE. Whilst the SOE will enhance the heat loss through the additional surface area available for convection, the heat conduction through the thermoelectric cooler (TEC) will be the

dominant cooling mechanism. The TEC model was matched against specifications given in the datasheet, and thermal interface properties were determined by fitting to experimental data on cell temperature at x70 optical concentration. Without any further fitting, this model then gave good fits to the TEC IV, the PV cell temperature vs TEC current and TEC current required to maintain 25 °C and 50 °C at 0–1000 W/m² illumination. This modelling allowed the key challenges of the thermal design of type A to be identified, shown graphically in Fig. 11. This indicates that very high temperatures may be experienced by the type A design under x300 optical concentration, due to the temperature drop across the PV cell to TEC interface, and the TEC itself. Type B was predicted to have a much lower operating temperature, due to the improvement of the PV cell to TEC interface and the improved thermal conductance of the TEC module, predominantly by increasing its area.

4. Electrical model parameters

Based on experimental I–V results, adding the SOE and POE have demonstrated a considerable improvement in the receiver electrical performance, especially in the current under STC. To characterize the favorable effect of SOE and POE on I–V curves quantitatively, we will add geometrical *CR* of SOE and POE into the current–voltage electrical model of the multi-junction modules presented in the paper, and extract SOE and POE optical intensity gain coefficients and the corresponding model parameters. Since the single-junction like method mentioned in the introduction is simpler and with a less number of parameters, it might potentially be applied in operational management of concentrating multi-junction PV cells/modules/arrays. This method is adopted in the paper.

4.1. Electrical model equation

For a multi-junction cell/module with SOE and POE, its complex internal electrical circuits can be represented by a lumped one-diode equivalent electrical circuit model, as shown in Fig. 12. Here the optical unit composed of POE and SOE is added on the top of the bare/flat PV cell. In this case, the mathematical expression for this equivalent circuit is written as [18]

$$I = I_{ph} - I_d \left[\exp\left(\frac{q(V + R_s I)}{nkT} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \tag{1}$$
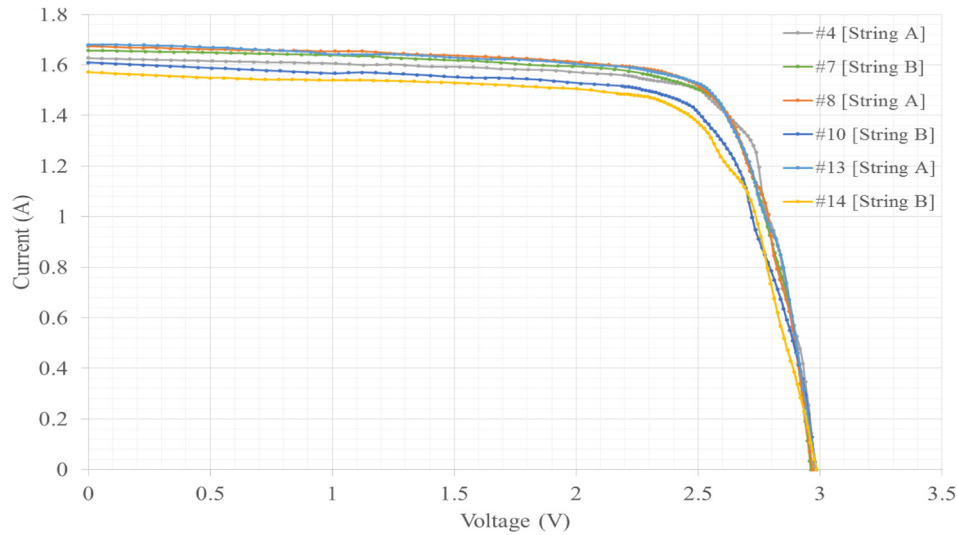
Fig. 9. Type B CPV-TE hybrid receivers tested under POE solar simulator at CEAEMA.

Table 3
Hybrid POE-SOE-CPV-TE receiver test data measured at CEAEMA.

Receiver	373-sun data					
ID	I_{sc} (A)	V_{oc} (V)	P_m (W)	FF (%)	η_{eff} (%)	SMR
Kappa	1.66	3.1	3.6	71	21.4	1.00
4	1.63	3.0	3.8	78	22.3	1.01
7	1.66	3.0	3.8	77	22.3	1.01
8	1.67	3.0	3.8	76	22.5	1.01
10	1.61	3.0	3.6	74	21.0	1.01
13	1.68	3.0	3.8	76	22.6	1.01
14	1.59	3.0	3.5	74	20.7	1.01
Mean	1.64	3.0	3.72	75.8	21.9	1.01

in which V and I are the output voltage and current of the PV cell/module respectively, q is the electron charge, $q = 1.60217646 \times 10^{-19}$ C, and k is the Boltzmann constant, $k = 1.38065031 \times 10^{-23}$ J/K, T is the cell temperature, I_d is the diode reversal saturation current, n is the diode quality factor, i.e. ideality factor, R_s is the combined series resistance and R_{sh} is the shunt resistance. I_{ph} is the photo current and depends on both radiation intensity S and cell temperature T. In the model Eq. (1), five variables such as I_{ph}, I_d, n, R_s add R_{sh} is the shunt resistance are model parameters and need to be determined with an experimental $I–V$ curve at STC ($S = 1000$ W/m², $T = 25$ °C).

Following the idea in [28], the SOE or POE or both are regarded as an optical intensity amplifier with a gain coefficient, m, such that the photo current, increased by the POE and SOE, is presented in terms of a power function of total concentration ratio and gain coefficient as follows

$$I_{ph} = CR^m I_{ph0} \qquad (2)$$

Substituting Eq. (2) into Eq. (1), the $I–V$ curve equation for the multi-junction PV cell/module with SOE or POE or both at STC is written as

$$I = CR^m I_{ph0} - I_d \left[\exp\left\{ \frac{q(V + R_s I)}{nkT} \right\} - 1 \right] - \frac{V + R_s I}{R_{sh}} \qquad (3)$$

Note that for the case without POE and SOE, $CR = 1$, Eq. (3) can restore the case without either SOE or POE. Eq. (3) represents a six-parameter lumped electrical model for a multi-junction PV cell/module with SOE or both SOE and POE at STC. Six parameters, I_{ph0}, I_d, n, R_s, R_{sh} and m in Eq. (3) need to be determined based on the experimental $I–V$ curves under three conditions; the first one for a PV cell/module without SOE or POE, the second one for the same PV cell/module with SOE, and the third condition for the same PV/cell/module with both

POE and SOE.

4.2. Method for determining six parameters

The trust-region-reflective (TRR) least squares algorithm provided in MATLAB [29] is employed to optimize the following objective function for the six parameters

$$f(I_{ph0}, I_d, n, R_s, R_{sh}, m) = \sum_{i=1}^{N_1} [(I_{1i} - I_{1i}^{exp})/I_{sc1}^{exp}]^2 + \sum_{i=1}^{N_2} [(I_{2i} - I_{2i}^{exp})/I_{sc2}^{exp2}]^2$$
$$+ \sum_{i=1}^{N_3} [(I_{3i} - I_{3i}^{exp})/I_{sc3}^{exp}]^2 \rightarrow \min \qquad (4)$$

where N_1, N_2 and N_3 are the numbers of experimental data of $I-V$ curves without optical unit, with SOE, with both SOE and POE, respectively; I_{1i}, I_{2i} and I_{3i} are the currents calculated from Eq. (3) with a set of temporary six parameters at the ith experimental voltages V_{1i}^{exp}, V_{2i}^{exp} and V_{3i}^{exp} in the cases without optical unit, with SOE, and with SOE and POE, respectively; I_{1i}^{exp}, I_{2i}^{exp} and I_{3i}^{exp} are the currents at the ith experimental voltages accordingly. The validation of the algorithm has been made in [28].

Once a set of six parameters are decided, the maximum electrical power will be tracked by minimizing the following objective function with the same optimization algorithm as above

$$f(I_{max}, V_{max}) = \frac{1}{IV} \rightarrow \min \qquad (5)$$

where I_{max} and V_{max} respectively are the current and voltage at which a maximum electrical power, P_{max}, is achieved.

4.3. Extracted six parameters

The six parameters of the PV cell were extracted based on its $I–V$ curves presented in Fig. 8 under $CR = 1$, 3 and 500 in the cases for bare cell, with SOE only and with both SOE and POE. To assess the error in $I–V$ curve fittings, the following errors are defined;

$$\begin{cases} \varepsilon = \frac{1}{3}(\varepsilon_1 + \varepsilon_2 + +\varepsilon_3) \\ \varepsilon_1 = \sqrt{\frac{\sum_{i=1}^{N_1}[(I_{1i} - I_{1i}^{exp})/I_{sc1}^{exp}]^2}{N_1}} \times 100\% \\ \varepsilon_2 = \sqrt{\frac{\sum_{i=1}^{N_2}(I_{2i} - I_{2i}^{exp})/I_{sc2}^{exp2}}{N_2}} \times 100\% \\ \varepsilon_3 = \sqrt{\frac{\sum_{i=1}^{N_3}[(I_{3i} - I_{3i}^{exp})/I_{sc3}^{exp}]^2}{N_3}} \times 100\% \end{cases} \qquad (6)$$
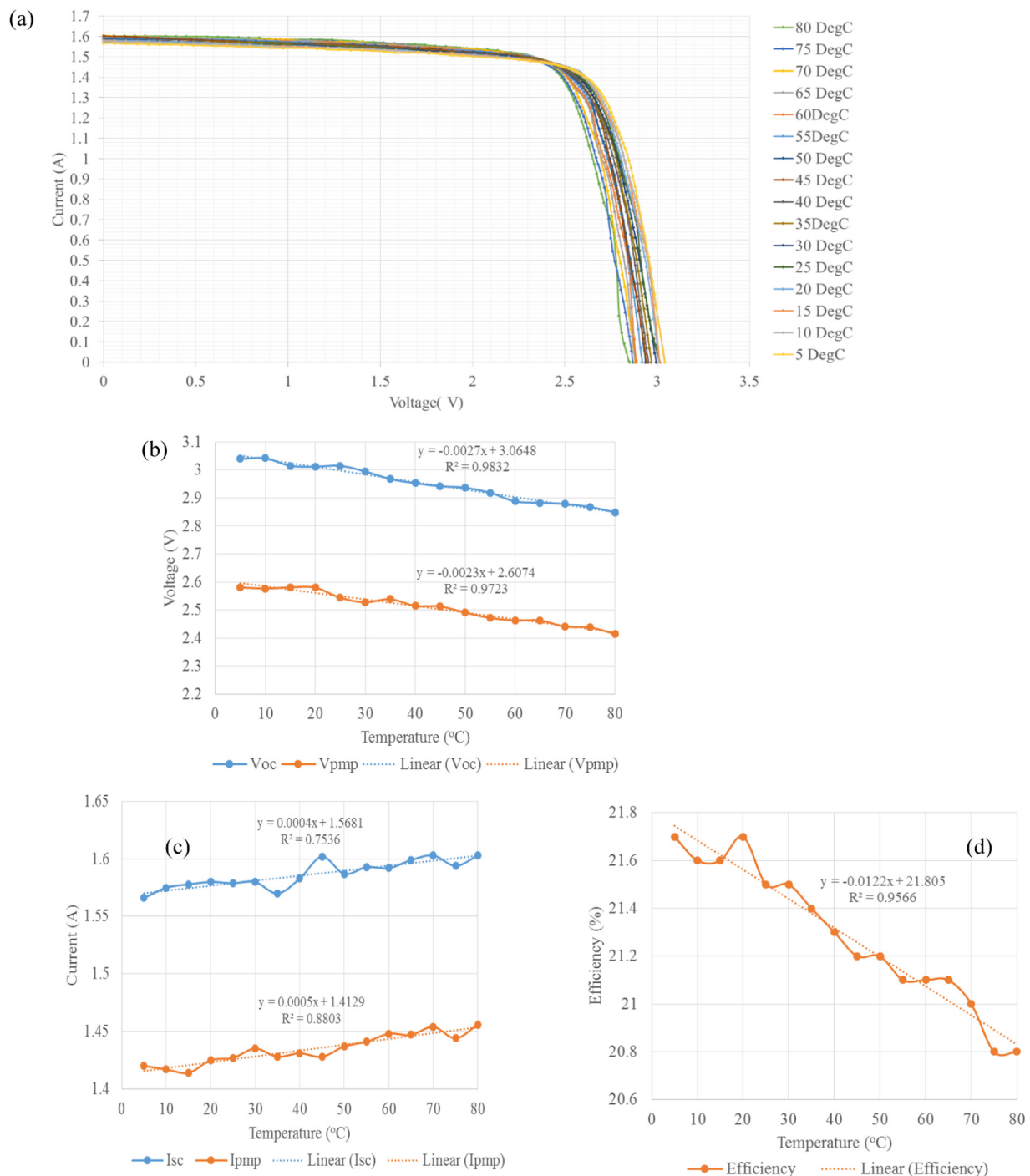
Fig. 10. I–V curve plots of receiver "9" (B) in 5 °C temperature steps (a). V_{oc} and V_{mpp} vs temperature curve (b). I_{sc} and I_{mpp} vs temperature curve (c) and CPV cell efficiency vs temperature curve (d).

where ε_1, ε_2 and ε_3 are the mean errors when the multi-junction cell is without any optical elements, with SOE only, and with both SOE and POE, ε is the arithmetic mean error of ε_1, ε_2 and ε_3.

Table 4 presents the range of six parameters during the parameter optimization process and their extracted values. For comparison, the extracted six parameters for monocrystalline PV cell with 1 CCPC, and monocrystalline PV modules respectively with 2×2, 9×9 CCPC in [28] are involved. A comparison of the predicted I–V curves is made against with the experimental I–V curves of type A in Fig. 13. The predicted I–V curves are basically in good agreement with the measurements with a mean error in current of 4.44%. It is shown that ε_1 and ε_2 are similar in values, but ε_3 is smaller than the other errors. These

errors might be associated with the assumed simple function of the optical gain response of SOE or POE and one-diode model adopted.

The errors in the short circuit current are -1.07, 6.54 and -5.74% for the cell without any optical elements, with SOE only, and with both SOE and POE, respectively, but the errors in the open circuit voltage are as small as 0.51, -0.10 and -0.55% for the cell. These errors are defined as the difference of the short circuit current or open circuit voltage predicted by the model from the corresponding experimental value, then divided by the experimental value and multiplied by 100%.

Compared with the optical intensity gain coefficient $m = (0.50–0.86)$ for CCPCs shown in Table 4, SOE or POE seems to have a larger gain coefficient (0.92), suggesting that the cells are subject to a
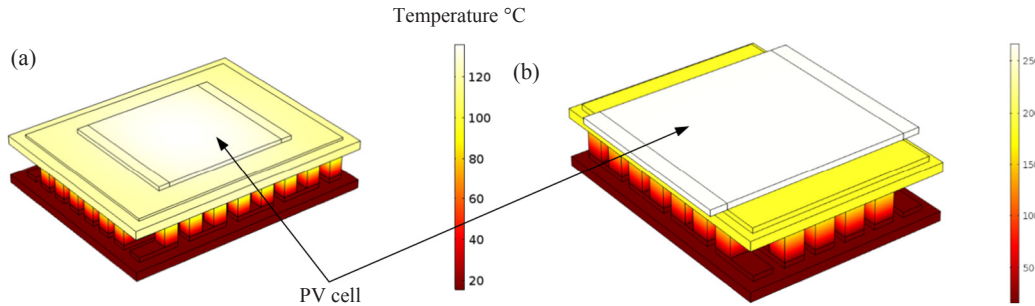
Fig. 11. Modelled temperature distribution of the PV cell and unpowered TE module under x300 optical concentration for (a) Type A and (b) Type B and C designs.
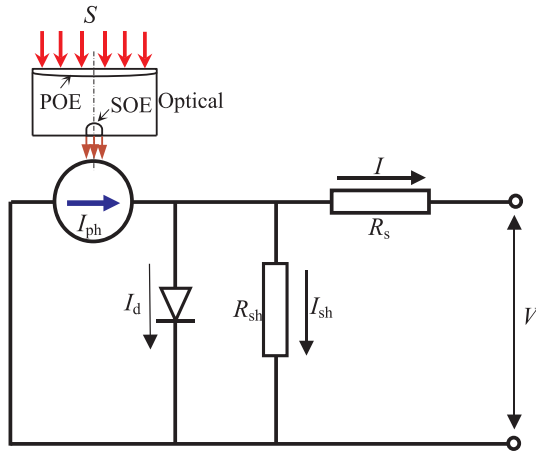

Fig. 12. Sketch of a lumped single-diode equivalent electrical circuit of the CPV cell with POE and SOE optics.

better optical efficiency. The values of I_d, R_s and R_{sh} don't show a significant difference from those for monocrystalline PV cell/modules.

5. Discussion

Hybrid CPV-TE receivers have been designed, developed, manufactured and characterized experimentally and theoretically in this work. The TE module geometry has been simulated and improved for higher thermal conductivity. The critical thermal interfaces between the cell and TE module have also been improved. The PCB design has been upgraded with calibration marks for SOE attachment together with tracks to minimize hot-spot formation. Two cells from two different triple-junction CPV wafers with very similar experimental probe data were selected for receiver manufacture (Kappa and #13 I_{sc} of 4.47 mA vs 4.48 mA, V_{oc} 2.26 V vs 2.19 V at 1-sun. I_{sc} 1.53A vs 1.46A, V_{oc} 2.80 V vs 2.81 V, fill factor 82% for both, cell efficiencies 33.8% vs 34.1% respectively under 330-suns). The receivers were manufactured using two different TE module geometries (type A and type B). The optical alignment of the type B receiver is an improvement on type A. This is inferred from the concentration ratios calculated from the Isc

measurements, x371 for Kappa and x375 for #13. Improvement in optical alignment and higher CR caused a higher cell temperature for #13 than for Kappa, in the order of 30 °C based on Voc measurements (3.1 V vs 3.0 V). The next step in this research will be to compare the performance of the thermoelectric modules, together with the CPV cell performance within type A and type B receivers. Identical thermal designs and optical concentration will be used to directly compare experimental results with the COMSOL model developed.

In the paper, we have extended previous work in [28] for monocrystalline PV cells/modules with CCPCs under a lower *CR*. The parameters in the six-parameter one-diode equivalent electrical model in [28] were successfully extracted based on a set of experimental *I–V* curves of a triple-junction type A CPV-TE receiver with bare cell, SOE and POE optical elements respectively. The models show a satisfactorily small error in current. The results in this paper confirm that the six-parameter electrical model is applicable for triple-junction PV cells/modules with optical concentrating elements at a higher *CR*. In this paper, a simple electrical model for a whole III:V multi-junction cell was used, limiting the information obtained about the electrical performance of three component sub-cells. Future work will investigate complex photon quantum calculation combined with a parameter extracting procedure proposed in [30]. This will disclose the electrical performance of the component sub-cells. As a long-term research aim, the scaling law which involves outdoor conditions such as [31] will also be investigated.

6. Conclusions

Novel hybrid CPV-TE receiver designs were manufactured and electrically, thermally and theoretically analyzed under secondary and primary optical concentration. Accurate optical alignment of both SOE and POE to the cell were found to be a critical factor in the current–voltage characteristics measured. Additionally, the receiver-case thermal interface and rear heat sink designs were also key to the CPV-TE hybrid module for both CPV cell and TE cooling performance. The integrated TE module successfully acted as both a temperature sensor and as a solid-state heat pump for the CPV cell, enabling characterization of the cell in 5 °C operational temperature steps. The experimental platform enabled accurate measurement of electrical

Table 4
The range of six parameters during optimization and the values extracted.

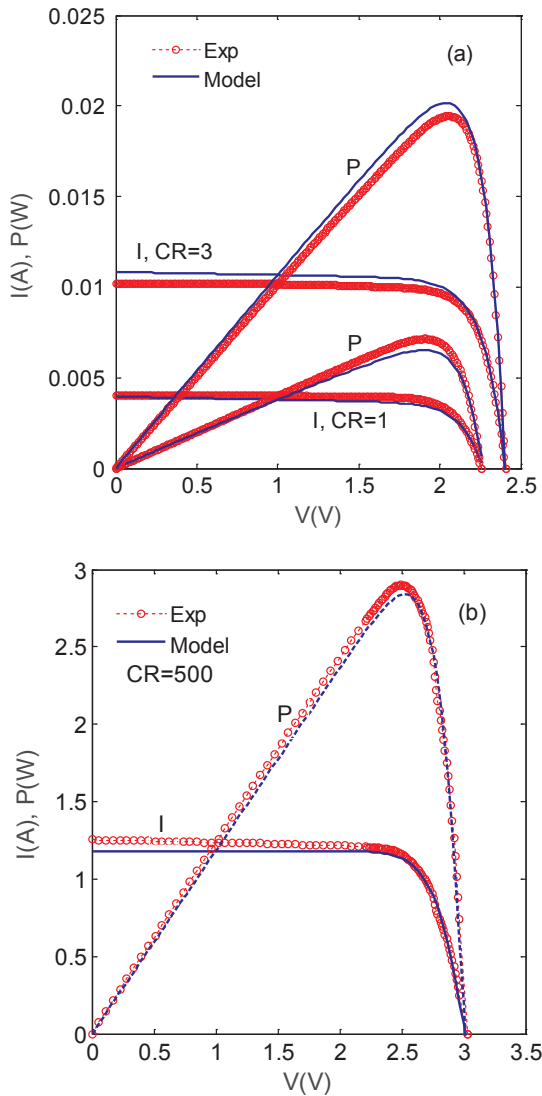| Parameter	m	n	I_{ph0} (A)	I_d (A)	R_s (Ω)	R_{sh} (Ω)
Range	[0, 1]	[0, 10]	[0, 10^{-2}]	[0, 10^{-7}]	[0, 0.1]	[0, 6000]
Extracted values	0.9171	4.2378	3.9564×10^{-3}	7.9030×10^{-11}	8.8647×10^{-2}	6000
Monocrystalline cell with 1 CCPC *	0.8611	1.101	2.8415×10^{-2}	1.6260×10^{-11}	4.5373×10^{-1}	6157.3
Monocrystalline module with 2 × 2 CCPC*	0.8234	3.1642	4.1385	1.3228×10^{-6}	1.6300×10^{-2}	1292.5
Monocrystalline module with 9 × 9 CCPC*	0.5099	10.015	4.4898×10^{-1}	4.7592×10^{-10}	3.5010×10^{-2}	6998.9
ε_1, ε_2, ε_3 and ε (%)	5.24 (bare), 5.00 (SOE), 3.09 (POE), 4.44 (arithmetic mean)					
Error in short circuit current (%)	−1.07 (bare), 6.53 (SOE), −5.74 (POE)					
Error in open circuit voltage (%)	0.51 (bare), −0.10 (SOE), −0.55(POE)					

Fig. 13. A comparison of experimental I–V curves of type A receivers with those predicted with model Eq. (1) and extracted parameters.

current–voltage characteristics under standard test conditions (1000 W/m^2 irradiance, 25 °C temperature and AM1.5D spectrum) and elevated temperatures, with linear temperature coefficients obtained over the 75 °C range tested.

A six-parameter single-diode equivalent electrical model was proposed for the multi-junction PV cells/modules and validated with the measured I–V curves of type A PV module at concentration ratios 1, 3 and 500 under the standard test condition based on an optimization method in MATLAB. The determined six model parameters have been compared with those of monocrystalline PV cells/modules with CCPCs. The model can fit the experimental I–V curves with a mean error of 4.44%, and the optical intensity gain coefficient of SOE and POE is very high, 0.92 in comparison with 0.50–0.86 for CCPCs. The extracted I_d, R_s and R_{sh} values do not exhibit a considerable difference from those for monocrystalline PV cell/modules. The model can be used in multijunction PV module development in the future. Further work includes sub-cells performance parameter identification for multi-junction PV modules with both SOE and POE. Photon quantum calculation in terms of solar spectrum and experimental I–V curves, and the scaling law development for outdoor conditions will be developed. The experimental and theoretical work presented in this paper can be used for further thermally-dependant CPV cell characterization (both STC and non-STC) conditions. This data will be used for future hybrid CPV-TE

device architectures to optimize electrical performance and device/system lifetime whilst minimizing levelised cost of energy at system level.

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