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Experimental characterization of a concentrating photovoltaic system varying the light concentration

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ABSTRACT

The concentrating photovoltaic system represents one of the most promising solar technologies because it allows a more efficient energy conversion. When a CPV system is designed, the main parameter which has to be considered is the concentration factor that affects both the system energy performances and its configuration. An experimental characterization of a CPV system previously realized at the University of Salerno, is presented in this paper considering several aspects related to the optical configuration, the concentration factor and the solar cell used. In particular, the parameters of an Indium Gallium Phosphide/Gallium Arsenide/Germanium triple-junction solar cell are investigated as function of the concentration factor determined by means of an experimental procedure that uses different optical configurations. The maximum concentration factor reached by the CPV system is 310 suns. The cell parameters dependence on the concentration is reported together with an electroluminescence analysis of the Indium Gallium Phosphide/Gallium Arsenide/Germanium cell. A monitoring of the electrical power provided by the system during its working is also presented corresponding to different direct irradiance values. A mean power of 2.95 W with an average efficiency of 32.8% is obtained referring to a mean irradiance of 930 W/m^2; lower values are obtained when the irradiance is highly fluctuating. The concentrating photovoltaic system electric energy output is estimated considering different concentration levels; the maximal obtained value is 23.5 Wh on a sunny day at 310×. Finally, the temperature of the triple-junction solar cell is evaluated for different months in order to evaluate the potential annual thermal energy production of the concentrating photovoltaic system.

1. Introduction

The concentrating photovoltaic system (CPV) constitutes an interesting solution in the field of the solar energy technologies [1]. In order to satisfy the energy demands of residential and industrial users, they represent an evolution of the traditional photovoltaic (PV) plants [2]. In particular, the CPV system is considered one of the most promising solar technologies allowing a more efficient energy conversion [3] and, then, a high decrease of the environmental pollution [4]. Moreover, they present an economically interesting solution with respect to the levelized cost of energy (LCOE), in particular under conditions where a high percentage of direct solar radiation is present [5]. Other technologies such as the flexible solar panels are also interesting [6], but they do not expect the solar concentration. Hence, the main characteristic of the CPV systems is to concentrate sunlight by means of optical devices decreasing the necessary solar cell area proportionally to the concentration factor (C) [7]. This parameter indicates how many times the solar radiation, incident on the primary optics, is concentrated on the solar cell [8]. Hence, it represents a key variable in the CPV system design, which affects both the system electric energy performances and its configuration. CPV systems employ multi-junction (MJ) solar cells, which present the highest electric efficiency among the solar cells [9]. On the one side the use of the MJ solar cell allows lower values of the charge–carrier thermalization losses and, then, stable operating temperatures but, on the other side, the increase of the sunlight concentration factor leads to an increase of the cell temperature. Overall a good electric power conversion efficiency can be achieved [10]. An active cooling of the cells would allow to increase the power conversion system efficiency further [11]. This constitutes a strategic factor of the concentrating photovoltaic and thermal systems (CPV/T). Such combined systems allow to produce simultaneously electric and thermal energy, exploiting the heat recovery from the solar cells [12]. So, referring to the thermal energy production, these systems allow a further reduction of the unitary costs [13]. The study

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Nomenclature

A	area (m^2)
C	concentration factor
CPV	concentrating photovoltaic
CPV/T	concentrating photovoltaic and thermal
D	diode
DC	direct current
DNI	direct normal irradiance (W/m^2)
EL	electroluminescence
FF	fill factor
h	height (cm)
I	current (A)
I_0	diode saturation current (A)
I-V	current-voltage
InGaP/GaAs/Ge	indium-gallium-phosphide/gallium-arsenide/germanium
InGaAs	indium-gallium-arsenide
k	Boltzmann constant
LCOE	levelised cost of energy
MJ	multi-junction
m	ideality factor
MJ	multi-junction
P	electric power (W)
PV	photovoltaic
R	resistance (Ω)
SMU	source measurement unit
T	temperature (°C)
TJ	triple-junction
x	suns
V	voltage (V)

Greek symbol

η	efficiency

Subscripts

c	cell
e	electron charge
i	sub-cell number
int	intermediate
kal	kaleidoscope
oc	open circuit
ph	photo-generated
s	series
sh	shunt
sc	short-circuit

of the CPV and CPV/T systems is mainly focused on two aspects: material adopted for the solar cells and the system configuration. The choice of materials for each sub-cell is traditionally determined by the requirements for lattice-matching between the different sub-cells [14]. Traditionally, in order to increase the optoelectronic performance, the MJ solar cells use multiple semiconductor materials with different band gaps to selectively absorb different wavelength ranges of the solar spectrum [15]. Currently, the power conversion efficiency of the MJ devices have reached values above 40% [16]. It should, however, be mentioned that completely different approaches for the achievement of conversion efficiencies above the detailed balance limit for single junction photovoltaic devices have been proposed. Just to mention one possible solution, the concept of the intermediate band solar cell has been introduced and first experimental realizations have been reported [17]. Today the most adopted solution for CPV and CPV/T systems is the triple-junction (TJ) solar cell [18]. This photovoltaic device represents one of the three main elements which compose such kind of systems [19]. In particular, they constitute the receiver which also includes the heat dissipation mechanism; active for a CPV/T system and passive for a CPV one [20]. The other two parts are the focusing optics and sun tracking system [21]. The optics are mainly subdivided in refractive or reflective solutions [1]. The first generally employs acrylic material lenses such as the Fresnel lens; the second uses mirrors. Since the concentrating systems operate only with the solar direct radiation component, a tracking system is required [22]. It allows to keep the receiver plane perpendicular to the sun rays at each moment. There are many types of concentrating systems that differ because of the components used and the configuration chosen: point-focus, line-focus and dense array. In point-focus systems each optic focuses the sunlight only on one cell; in line-focus systems the concentration takes place along a line where MJ cells are usually arranged. Finally, the dense array systems usually concentrate solar radiation on a series of cells arranged side by side. The adopted configuration affects the achievable concentration level and therefore also the system performances. Hence, the study of the behavior of the TJ cells under concentration is basic for the analysis of a CPV system. The cell characterization under different working conditions allows to predict the system energy production. For this purpose, an optic configuration that allows to change the incident radiation is needed. Moreover, as reported by Fernández and Almonacid [23], the study of the TJ cell temperatures during the operating is important in order to evaluate the potential thermal energy production of the system. In [24] the thermal and electrical characteristics of a Indium Gallium Phosphide/Gallium Arsenide/Germanium (InGaP/GaAs/Ge) TJ solar cell under a two-stage concentration have been investigated. In this case the solar cell has been additionally cooled by a heat pipe and a homogenizer is introduced in order to make the light spot more uniform. In [25] the dependence of the MJ solar cell parameters on concentration and temperature are analyzed by curve fitting of the experimental current-voltage (I–V) characteristics applied to the model equation of the single diode cell. García-Domingo et al. in [26] have employed a multilayer perceptron model in order to generate the I-V characteristic curves of a CPV module, considering the atmospheric variables influence. In [27] the performances of two CPV devices of 3.5 kWp have been investigated. Each system uses TJ cells whose active area is 5.5×5.5 mm^2 and a total geometrical concentration ratio of 476× is reached by means of Fresnel lens. In [28] the spectral sensitivity of a concentrating TJ solar cell are investigated. In this case also the effects of atmospheric parameters on electrical and thermal performances of the solar cell have also been reported. Chemisana et al. [29] describe a photovoltaic-thermal generator combining a domed linear Fresnel lens as primary concentrator, a compound parabolic reflector as secondary concentrator and a photovoltaic-thermal module. Finally, in [30] the experimental results of a miniature fiber-optic photovoltaic concentrator with a solar cell completely passive cooling, have been reported. The results include the conversion efficiency of the tandem III–V cells and show the influence of the achieved concentration levels. Hence, in order to investigate the performance of a CPV system both the material used as active layer in the solar cell and the adopted configuration should be considered. In this paper an experimental characterization of a CPV system, realized previously at the University of Salerno [31], is presented. The analysis takes into account several aspects related to the optical configuration, the achieved concentration factor and to the type of used solar cell.