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A home-made system for incident photon-to-electron conversion efficiency (IPCE) characterization, based on a double-beam UV-Vis spectrophotometer, has been set up. In addition to its low cost (compared to the commercially available apparatuses), the double-beam configuration gives the advantage to measure, autonomously and with no need for supplementary equipment, the lamp power in real time, compensating possible variations of the spectral emission intensity and quality, thus reducing measurement times. To manage the optical and electronic components of the system, a custom software has been developed. Validations carried out on a common silicon-based photodiode and on a dye-sensitized solar cell confirm the possibility to adopt this system for determining the IPCE of solar cells, including dye-sensitized ones. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4904875]

I. INTRODUCTION

Coal, petroleum, and other fossil fuels have inadequate availability for long-term needs, and it is hence necessary to rethink the energy production landscape in sustainable terms. In this scenario, solar energy is considered one of the most promising ways to solve the global energy and environmental problems.[1] In turn, one important branch of solar energy is photovoltaics (PV), i.e., the direct conversion of solar energy into electricity. The current PV technology is based mainly on silicon, but novel materials and concepts are gradually emerging, like calchogenides (CIS and CIGS technologies, Cadmium Telluride), dye-sensitized solar cells (DSSCs), organic solar cells, perovskite-based solar cells, and so on.[2–5] In order to assess the actual performances of solar cells, J/V (current density/voltage) measurements in illuminated conditions are carried out to determine the short circuit current density (J_{SC}), the open circuit voltage (V_{OC}), and the fill factor (FF). The fill factor can assume values between 0 and 1 and is defined as

$$FF = (V_{max} \cdot J_{max})/(V_{OC} \cdot J_{SC}), \qquad (1)$$

where V_{max} and J_{max} are voltage and current density measured at the cell maximum power point. Together with the optical power density incident on the cell (I_0), these parameters contribute to define the overall cell efficiency η.

$$\eta = V_{OC} \cdot J_{SC} \cdot FF / I_0. \qquad (2)$$

A further PV device characterization technique is the Incident Photon-to-Electron Conversion Efficiency (briefly, IPCE) measurement. IPCE is defined as the ratio between the number of photogenerated charge carriers in short-circuit conditions (recovered at the device electrodes) and the number of photons

incident on the measured device at a given wavelength. It is usually determined by illuminating the solar cell with monochromatic light covering the investigated spectral range and measuring the short-circuit current at each wavelength, although even more complex methods have been developed.[6–8] In more quantitative terms, the IPCE value corresponds to the short circuit current density (J_{SC}) produced under (ideally) monochromatic illumination of the cell, divided by the incident radiative flux (Φ_λ) that strikes the cell at that wavelength. According to this definition, the IPCE (as a function of the incident wavelength λ) can be calculated as

$$
\begin{aligned}
IPCE(\lambda) &= \frac{\text{\# of photogen.electrons}}{\text{\# of incident photons}} \\
&= \frac{Jsc(\lambda)}{\Phi(\lambda)} \cdot \frac{hc}{e} \cdot \frac{1}{\lambda} \\
&= \frac{Jsc(\lambda)}{\Phi(\lambda)} \cdot 1240 \cdot \frac{1}{\lambda} = R(\lambda) \cdot 1240 \cdot \frac{1}{\lambda}, \qquad (3)
\end{aligned}
$$

where R is the device spectral responsivity (defined as the ratio between electrical output, expressed in amperes, and the optical input, expressed in watts[9]), h is the Planck's constant (6.626×10^{-34} m^2 kg s^{-1}), c, the light speed (2.998 m s^{-1}), and e, the electron charge (1.602×10^{-19} A s). This characterization technique can be extremely useful, since in IPCE experiments, the charge recombination due to opposite charges' annihilation is minimized due to the relatively small number of photons (and hence of photogenerated charges) that reaches the cell in the measurement conditions. These conditions can deliver some understanding of internal phenomena occurring in the devices.

For DSSCs, whose internal physical processes are not yet fully understood, the IPCE-generated information could allow, for example, to extract important device information like the electron diffusion length.[10,11]

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However, parameters like the incident light power, which affect internal processes like charge recombination at interfaces or local heating, influence markedly the measured IPCE of these devices, varying its magnitude and even the shape of the IPCE-λ curve. Therefore, IPCE measurements on DSSCs are rather sensitive experiments, and the conditions in which they are carried out must be carefully tuned and controlled in order to obtain an IPCE determination useful for comparisons with other devices.[12–14]

On the other hand, IPCE measurements are not very diffused (likely due to the high cost of IPCE setups that can get over 70 k€), and this hinder a standard definition of the IPCE measurement procedures and conditions, especially for DSSCs, which are not yet an established technology.

IPCE setups are usually constituted by a single beam optical system (a light source emitting in the UV-Vis range and a monochromator that selects the wavelength to be sent on the sample PV cell) and by a precision amperometer, connected to the PV cell. Other optical and electronic tools, such as signal switches, lock-in amplifiers, and so on, complete the standard characterization system. In general, the cost of the optical system alone can vary from 15 to 50 k€. In order to have a complete IPCE characterization system, a further cost for a precision amperometer (which, alone, can span from a few to 10-20 k€) must be added. With respect to the performances of the optical systems, it must be considered that the light sources get degraded over operative time, hence a calibration of the instrument lamp with a calibrated photo-detector is recommended before any characterization session. This means that in a standard commercially available IPCE system with a single beam configuration, any solar cell characterization should be preceded by a lamp power calibration at each wavelength in order to deliver a reliable response. This step is usually time-consuming, and this, together with the not negligible cost of commercially available systems, limits the diffusion of IPCE measurement setups. In order to overcome these issues, home-made IPCE systems with a standard single beam approach based on Xe lamps[15] or with a more refined wavelength-tunable LED-array source including a self-calibration system based on an optical fiber coupled to a reference photodiode,[16] have been proposed.

On the other hand, conventional UV-Vis double-beam spectrophotometers are widely diffused in research laboratories and are becoming less and less expensive (double beam UV-Vis spectrophotometers are currently commercially available at a price below 10 k€). These instruments have very good monochromators and allow an easy and accurate control of the used wavelength range. Moreover, the built-in double light beam offers, in theory, the possibility of concurrently reading the optical power originated by the system lamp (with one beam) and performing the actual illumination of the measured device (with the other one). Therefore, UV-Vis double-beam spectrophotometers could allow to (i) work with highly accurate monochromatized beams, (ii) measure the lamp emission in real time during the PV cell testing (hence avoiding time-expensive calibration), and (iii) obtain the previous two results via a conveniently low-cost equipment. The proper coupling of the optical system of such an instrument to an amperometer, which is able to

extract from the tested PV cell the photocurrent generated upon emission from the monochromatized source, would hence allows to obtain an accurate and fast instrument for the IPCE determination at very low costs. Considering that double-beam UV-Vis spectrophotometers are usually available in laboratories dealing with PV devices, this approach could greatly help spreading the IPCE measurements, paving the way for widely diffused comprehensive characterization and more standardized evaluation of PV devices, including emerging ones like DSSCs.

In this view, we report on the setup of a complete IPCE measurement system for PV cells based on (i) a common UV-Vis spectrophotometer and (ii) a precision current measuring unit. In order to manage the optical and electronic instruments, a user-friendly software written in National Instruments LabVIEW® environment has been developed.[17] The procedures related to the setup of the optical system and to the real time calibration of the light source, and practical issues arisen and solved during the system development are exposed and discussed. Finally, the effectiveness of this home-made IPCE measurement system has been validated by tests performed on a silicon photodiode with known spectral response and on a DSSC fabricated for these tests using commercially available materials.

II. EXPERIMENTAL SETUP

A. Instruments

An IPCE characterization system has been setup assembling a double beam UV-Vis spectrophotometer (Lambda 35, Perkin-Elmer) and a digital multi-meter (Model 2400, Keithley). The optical architecture of the Lambda 35 is reported in Fig. 1(a). The determination of the spectrometer lamp power has been carried out using a calibrated photo-detector (818-UV, Newport). A standard silicon photodiode (SFH 2430, OSRAM Opto Semiconductors) was used to validate the IPCE system, together with a by-purpose fabricated DSSC (see Sec. II D).

B. Software

A complete user-friendly software in LabVIEW 8.6 environment has been developed to manage the IPCE system. An independent executable of the LabVIEW software ("Home-IPCE.exe") running under Microsoft Win XP is available as supplementary material and is usable free of charge, provided that this paper is cited in the publications that will take advantage of the software.[17] The command lines used in LabVIEW for controlling the spectrophotometer are described in the Perkin-Elmer instructions manual.

Legend for both Figs. 1(a) and 1(b): L1 = halogen lamp; L2 = deuterium lamp; G = monochromator; S1 and S2 = slits; FW = filters wheel; BS = beam splitter; O1 and O2 = lenses; A1 = attenuator; D1 and D2 = detectors; M1 = folding mirror lamp change; M4, M5 = ellipsoidal mirrors; M2 = toroidal mirror; M3 = spherical mirror. In IPCE configuration (b), the different position of the slits (S1 and S2) is underlined by a color code (grey = partially closed slit; white = open slit).
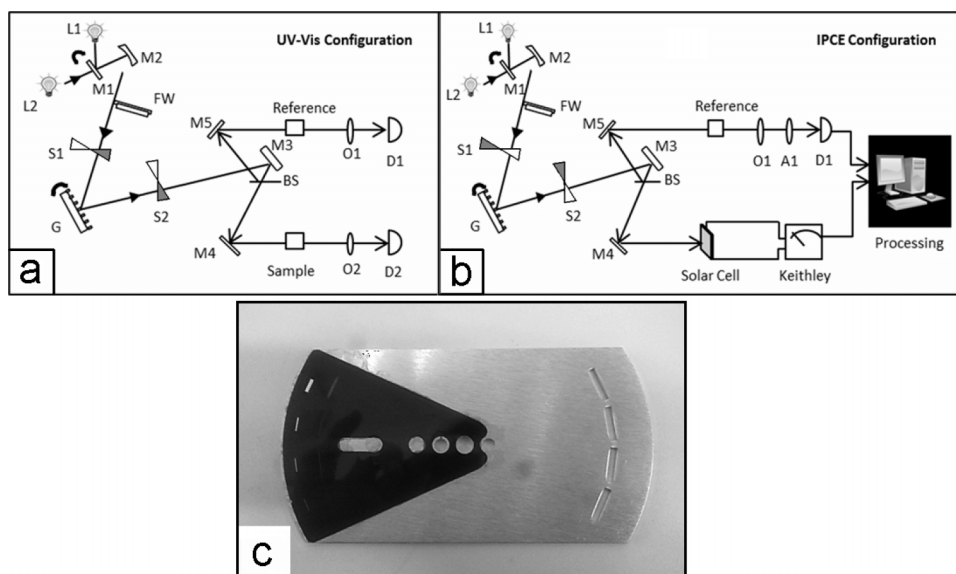
FIG. 1. (a) A schematic view of the double-beam UV-Vis spectrophotometer used for this work. (b) Scheme of the same instrument modified in order to work as an IPCE-measuring system. (c) A photograph of S1/S2 slit.

C. Measurements

A few practical aspects of the performed measurements are highlighted below.

(i)   A dedicated sample holder (see Fig. 2(b)) has been fabricated to hold correctly in place the sample to be measured (solar cells or photodiode) in the measure d sample compartment (see Fig. 1(b)). The measurements have been carried out using shielded cables between the PV cell and the multi-meter to minimize the electrical noise.

(ii)   All the reported IPCE measurements have been made at 2 nm wavelength intervals, between 400 and 1000 nm.

(iii) The spectrophotometer's lamps have been switched on at least half an hour before any measurement session to allow beam stabilization.

D. Dye-sensitized solar cell fabrication

The DSSC used for validating the IPCE system was fabricated using titanium dioxide/fluorine-doped tin oxide electrodes (Solaronix 74 101 titania electrodes, opaque).

The TiO_2 electrode has been heat treated at $450\,°C$ for 30 min, allowed to cool down to about $80\,°C$ and then immersed into a 0.3 mM solution of di-tetrabutylammonium *cis*-bis(isothiocyanato) *bis*(2,2′-bipyridil-4,4′-dicarboxylate) ruthenium(II) (N719 dye, Aldrich) in a mixture ethanol:*t*-butanol = 3:1 (ethanol, anhydrous, Carlo Erba Reagenti; *t*-butanol, 99.5%, Acros Organics). The electrodes were left in this mixture overnight. A drilled and FTO-platinum counter electrode (Solaronix, 74 201) has been coupled with the dye-sensitized TiO_2 electrode, and the two were sealed together in a sandwich configuration using a hot-melt polymer (Surlyn®, DuPont). The inter-electrode space was filled using an iodide/tri-iodide-based electrolyte (HI-30, Solaronix), and the cell was sealed using a small piece of hot-melt polymer and a cover glass.

III. RESULTS AND DISCUSSION

A. UV-Vis spectrophotometer and IPCE system: A reversible conversion

A schematic representation of the optical architectures of the UV-Vis spectrophotometer and of the final IPCE setup
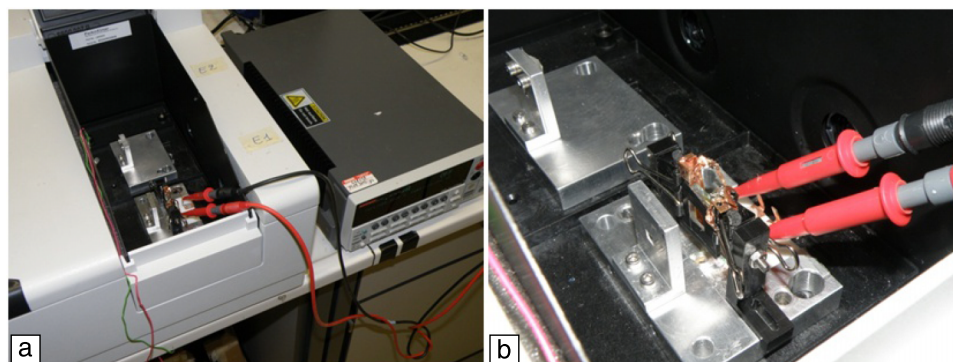

FIG. 2. Photos of the spectrophotometer compartments in the IPCE measurement configuration of the home-made IPCE system. (a) The amperometer is connected to the device to be measured in the sample compartment of the UV-Vis spectrophotometer. (b) In order to have a homogeneous incident beam on both the D1 photodiode and on the cell to be measured, two aluminum windows have been mounted in both compartments.

is shown in Figs. 1(a) and 1(b), respectively, to which the following labels refer. The light sources consist of a pre-aligned deuterium (30 W, L2) and tungsten-halogen (55 W, L1) lamps. A monochromator holographic concave grating (G) allows the selection of the desired wavelength (s). The instrument slits S1 and S2 are constituted by metallic disk portions, in each of which two sets of apertures are directly dug in the metal, placed on the right and on the left of the disk (Fig. 1(c)). In addition, on the left side of the disk portion, a supplementary set of plastic masks, each of which delivers a different final aperture that corresponds to a different spectral resolution (from 0.5 to 4 nm) is placed (Fig. 1(c); see also grey triangles in Figs. 1(a) and 1(b)). The beam splitter (BS) has the function of splitting the beam exiting from the slits in two components, each one of approximately equal intensity. The two twin beams are hence directed in real time towards the photo-detectors D1 and D2 (Fig. 1(a)). Preliminary tests aimed at verifying the suitability for IPCE measurements of the beam power hitting the D2 photodetector in the standard UV-Vis spectrophotometer configuration were carried out using a Newport calibrated photodiode. The photodiode was positioned along the path of the beam incident on the D2 photodetector, in the sample compartment (Fig. 1(a)/1(b)). However, none of the selected standard slits allowed us to record sufficiently clean (i.e., low-noise) signals, due to the relatively low power of the halogen lamp (55 W; it has to be considered that in commercial IPCE setups the halogen lamp power varies from 100 to 300 W). Therefore, upon suggestion of Perkin-Elmer (PE) technical personnel, we performed a manual exchange of the slits' configuration. The slits' disks were physically detached from their linchpins and re-mounted inverting their left and right side, so as to have the unobstructed slits (i.e., those not covered by the plastic, visible on the right of Fig. 1(c)) exactly on the path of the light beam (see Fig. 1(c), and compare the grey and white sides of the slits in Figs. 1(a) and 1(b)). With this simple and rapidly reversible hardware modification (the whole operation takes less than five minutes, and the slits can be taken back to their original configuration in the same time), the amount of light transmitted by the spectrometer was found to be more than sufficient to obtain signals corresponding to light power well over 1 μW per each wavelength, with satisfactory signal-to-noise ratio. However, when moving from the calibrated photodiode to the spectrophotometer D1 detector, evident signal saturation was found due to the much higher sensitivity of the latter with respect to the first one. On the other hand, keeping the standard slit did not allow to obtain sufficiently high beam power. This conundrum was solved by using the unobstructed slit and placing an optical attenuator in the reference sample compartment in order to filter the beam impinging on D1 photo-detector. The filter characteristic has been determined performing experiments with and without the attenuator with the help of a calibrated photodiode, as described in Sec. III B 1. No other modifications of the spectrophotometer were necessary for proceeding over with the actual IPCE measurements. Overall, the whole set of hardware modifications (slit change, optical attenuator addition) does not take more than five minutes and is fully reversible. During standard UV-Vis measurements, the sample

compartments are occupied by a reference sample and by the sample to be measured (see Fig. 1(a)), while in the IPCE configuration, the reference sample compartment is empty and the measured sample compartment is occupied by the PV cell/photodiode to be characterized, to which an external precision amperometer is connected (Fig. 2).

From a practical point of view, though the possible operative range of the Lambda 35 is 190-1100 nm, for this work, we focused only on a portion of the available emission spectrum (400-1000 nm), which is the one of interest for the solar cells used for the system validation.

B. IPCE measurements overview

The Home-IPCE software calculates the IPCE as a function of the device responsivity (see Eq. (3)). In order to do so, it is necessary to acquire the values of the current photogenerated by the device and of the optical power incident on the same. The former datum is obtained by a simple reading of the amperometer connected to the analyzed device. With respect to the optical power incident on the device, in a single beam instrument, these values (i.e., the beam intensity at each wavelength) would be determined at the beginning of the measurement for the whole set of tested wavelengths, during a dedicated calibration step, then stored in the instrument's memory and recalled at the end of the measurement to compute the final IPCE values. On the contrary, the configuration of a double beam spectrophotometer offers the possibility to check this optical power at each single wavelength in real time, since the already monochromatized beam is split into two almost identical "reference" and "sample" beams (incident on photodiode D1 and on the cell, respectively). This option allows to get rid of any possible problem deriving from lamp degradation phenomena that would be reflected in even slight changes in the optical power impinging on the measured device and/or from temporary optical power oscillations due to external factors. To take advantage of this possibility, we devised experimental procedures divided into two independent routines, i.e., "Calibration" and "Measurement."

1. Calibration

Although the double beam allows to calculate, in real time, the actual power incident onto the probed PV device, a first calibration step is needed to calculate the reference proportionality constants that will be used to measure the lamp power in real time. This step has to be performed, in principle, only once. The only reason for repeating it is an exceptional event, like the change of the lamp or of an optical component of the spectrophotometer. The calibration is accomplished by retrieving from the Lambda 35, the information about the lamp power incident onto the D1 detector at each selected wavelength (see Figs. 1(a) and 1(b)). This determination was not trivial due to the necessity to characterize the D1 detector response in order to obtain the desired data. In fact, the direct connection of D1 to a power-meter was physically impossible due to the spectrophotometer construction characteristics, since the D1

detector is a *unicum* comprising a silicon photodiode and a more complex electronic system that transduces the incident photons into an electrical signal. To deal with these issues, it was considered that the PE proprietary software "UV Winlab," that comes with the spectrophotometer, gives the reading of the D1 response upon illumination under the form of "*counts*," as termed by UV Winlab. We were not able to directly infer any meaningful current or power response of D1 from the *counts* reading. Therefore, in order to understand the mathematical correlation between the *counts* incident on D1 photodiode and the lamp power incident on the cell, we carried out the following tasks:

(a): A Newport calibrated photodiode was placed in the reference compartment and electrically connected to a precision amperometer. The optical power $W_{(\lambda)Newport}$ incident on the calibrated photodiode was then calculated for each selected wavelength (with and without attenuation filters), by means of the known responsivity of the photodiode, using Eq. (4):

$$W_{(\lambda)Newport} = I_{(\lambda)meas}/R_{(\lambda)Newport}, \tag{4}$$

where $I_{(\lambda)meas}$ is the current measured at the photodiode by means of the amperometer and $R_{(\lambda)Newport}$ is the photodiode responsivity (available from the Newport data sheet). At the completion of this task, we obtained a table reporting the lamp power at each selected wavelength, which was used for the subsequent calculations.

(b): Attenuation factors $\alpha(\lambda)$, for the different filters used in Task 1, were calculated as the ratio between the filtered lamp power and the "naked" (not filtered) lamp power.

$$\alpha_{(\lambda)} = \frac{W_{(\lambda)Newport}\,(filtered)}{W_{(\lambda)Newport}\,(not\ filtered)}. \tag{5}$$

(c): The D1 photodiode $counts_{(\lambda)D1}$ (readings at the D1 photodiode as given by the UV Winlab software at the considered wavelength) were related to the incident lamp power by a proportionality factor assumed to be linear at different lamp powers. The validity of this assumption was confirmed via transmittance measurements using attenuators with different thicknesses that showed that the lamp power incident on the D1 photodiode was reduced linearly with the variation of the attenuator thickness (hence of the attenuation coefficients) along the whole range of wavelengths considered. The coefficient $k_{(\lambda)}$ that correlates counts to incident lamp power was therefore calculated

$$k_{(\lambda)} = \frac{W_{(\lambda)Newport}(no\ filter)}{counts_{(\lambda)D1}\,(no\ filter)}$$
$$= \frac{W_{(\lambda)Newport}(filter\ a)}{counts_{(\lambda)D1}\,(filter\ a)}$$
$$= \frac{W_{(\lambda)Newport}\,(filter\ b)}{counts_{(\lambda)D1}\,(filter\ b)}. \tag{6}$$

The so-obtained $k_{(\lambda)}$ values have been corrected by the attenuation factor $\alpha_{(\lambda)}$, and the resulting values of $k'_{(\lambda)} = k_{(\lambda)}/\alpha_{(\lambda)k}$ have been used to determine the actual lamp power $W_{(\lambda)Actual}$ incident on the cell in sample compartment in the following Eq. (7):

$$W_{(\lambda)Actual} = \frac{W_{(\lambda)D1}}{\alpha_{(\lambda)}}$$
$$= \frac{k_{(\lambda)} \cdot counts_{(\lambda)D1}}{\alpha_{(\lambda)}} = k'_{(\lambda)} \cdot counts_{(\lambda)D1}. \tag{7}$$

2. IPCE measurement procedure

The procedure starts with the instruments' initialization and user inputs (that include wavelength range, scan speed, spatial resolution, multi-meter compliance values, and active area of the cell—Fig. 3(b), block 1). When the measurement procedure starts, the Home-IPCE software tells the instrument to change the wavelength of emission according to the user's input (Fig. 3(b), block 2). After this, the software tells the multi-meter to read the current photogenerated by the
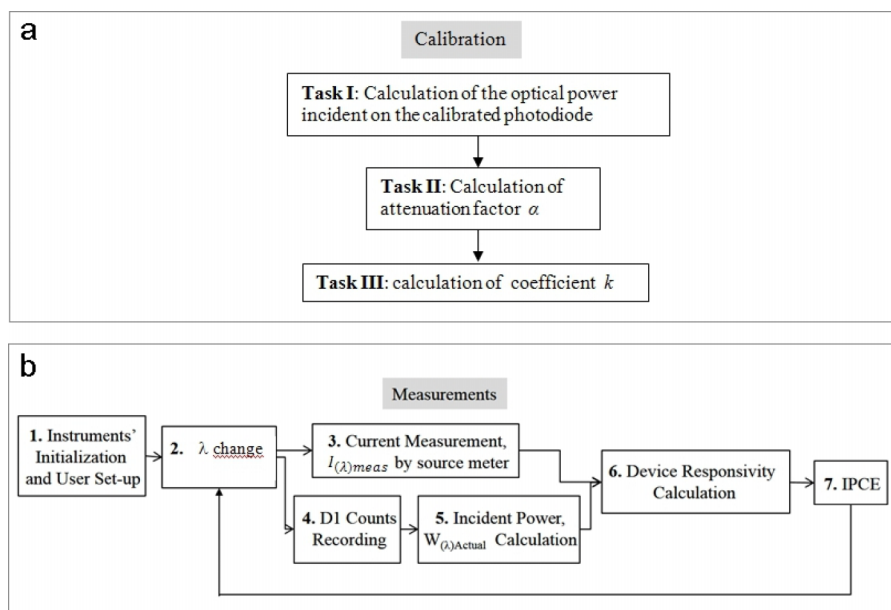

FIG. 3. (a) Visual description of logical steps involved in the calibration and (b) in the IPCE calculation.

measured device, $I_{(\lambda)pg}$ (Fig. 3(b), block 3), keeping this value in a dedicated memory cell, and it reads the *counts* number from the $D1$ photodiode of the spectrophotometer (Fig. 3(b), block 4). Coupling this latter datum with the corresponding $k_{(\lambda)}$ and $\alpha_{(\lambda)}$ values (that were stored in memory in the calibration step), the software calculates, in real time, the exact power incident on the measured device $W_{(\lambda)Actual}$ (Fig. 3(b), block 5), using the Eq. (7).

The so-calculated optical power incident on the device is then used to compute the device responsivity $R_{(\lambda)}$ (Fig. 3(b), block 6) according to Eq. (8)

$$R_{(\lambda)} = I_{(\lambda)pg}/W_{(\lambda)Actual}, \tag{8}$$

and finally the IPCE, according to Eq. (3) (Fig. 3(b), block 7). This loop is then repeated until the final wavelength set at the beginning of the Home-IPCE software routine (Fig. 3(b), block 1) is reached, and both a table in ASCII code (.txt file) with the IPCE vs. wavelength data and a graph showing the device IPCE are created.

C. IPCE system validation

In order to validate the effectiveness and reliability of the discussed home-assembled IPCE system, a standard silicon-based photodiode (purchased from Osram) and a DSSC have been measured. The IPCE curve of the photodiode, determined as described in Sec. III B 2 (solid line), together with the same characteristic as given by the supplier (filled triangles) are shown in Fig. 4. As it can be seen, the data obtained using the IPCE system described here are in good agreement with those given by the photodiode constructor.

The IPCE system has been tested also on a DSSC, fabricated using commercially available materials as described in the experimental part. The cell gave, under an AM 1.5G simulated solar spectrum, an overall efficiency of 4.9%, with a J_{SC} of 10.4 mA/cm^2, a V_{OC} of 0.7 V, and a FF of 67%. The IPCE curve measured with the developed system showed a maximum of 90% at 530 nm (Fig. 4(b)) and a curve shape resembling that of analogous devices measured in analogous conditions.[12,13,18]

The determination of a PV cell short circuit current density J_{SC} can be (a) directly measured via standard J-V measurements carried out under an AM 1.5G solar simulator (J_{SC} (J-V)) or (b) obtained integrating the product of responsivity $R(\lambda)$ and sun spectral irradiance $E(\lambda)$ at AM 1.5G-equivalent conditions, i.e., integrating the product of $IPCE(\lambda)$, elementary charge q, and solar spectral photon flux $\Phi(\lambda)$ at AM 1.5G, within the considered wavelength range[13,18] (J_{SC} (IPCE)). In particular, the approach to J_{SC} calculation described in (b) can be implemented using the following Eq. (9):

$$
\begin{aligned}
Jsc(IPCE) &= \int_{\lambda a}^{\lambda b} R(\lambda) \times E(\lambda)d\lambda \\
&= \int_{\lambda a}^{\lambda b} IPCE(\lambda) \times q \times \Phi(\lambda) \times d\lambda. \tag{9}
\end{aligned}
$$

For the considered DSSC, it is hence possible to calculate J_{SC} (IPCE) = 12.8 mA/cm^2, which is higher than the J_{SC} (J-V) = 10.4 mA/cm^2. Discrepancies like this are known in the field of DSSCs and are up to now explained in terms of phenomena involving the cell electrolyte or other factors,[14,19,20] although in our case we interpret the higher J_{SC} (IPCE) as an indication of an important charge carriers recombination occurring in the tested cell.

IV. CONCLUSIONS

In conclusion, we have reported on how a normal UV-Vis spectrophotometer can be converted into the optical part of a home-made IPCE system. Notably, this conversion is implemented in a fully reversible fashion, i.e., the so-obtained optical part of the IPCE system can be converted back to the original UV-Vis spectrophotometer (whose performances are not affected by this change of use), with a minimally invasive hardware change. This "UV-Vis/IPCE and vice versa" functionality switch can be carried out in minutes, preserving the work capabilities for the laboratories in which the system is implemented. The so-developed IPCE system has been validated using a commercial photodiode and a home-fabricated DSSC, and in both cases, the response of the system was more than satisfactory. An executable LabVIEW software integrating the spectrophotometer and a Keithley 2400 voltage source/amperometer for delivering a complete IPCE system was developed[17] and is made available free of charge (Creative Commons License CC BY-NC) to anyone interested in the matter, provided that the work presented here is cited in further
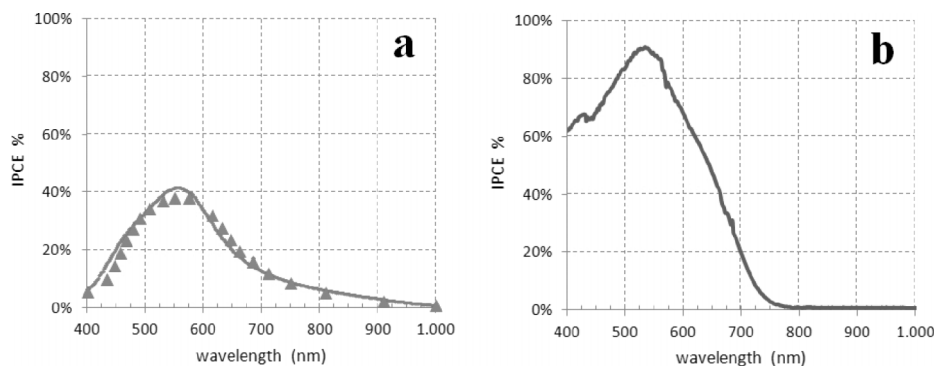

FIG. 4. IPCE curve of (a) a silicon-based photodiode (filled triangles: values from technical datasheet; solid line curve: values measured using the developed IPCE setup); (b) a DSSC measured using the developed IPCE setup.

papers taking advantage of the described home-made IPCE system.

ACKNOWLEDGMENTS

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