Small-Signal Modeling and Parameter Extraction Method for Photovoltaic Cell Integration in Indoor Visible Light Communication Systems

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Abstract— Photovoltaic (PV) cells are being adopted as a viable and cost-effective option for implementing receivers within Visible Light Communication (VLC) systems, primarily in indoor environments. Accurately estimating the generated current and voltage of the PV cell based on incident light is crucial when designing VLC systems. For this assessment, the 1D2R electrical equivalent model, which incorporates a diode and two resistors, is employed. In AC small signal analysis, the diode is substituted by its dynamic counterpart, which comprises a dynamic resistance in parallel with an equivalent capacitance. This study introduces an approach to measure and characterize the small-signal parameters of a PV cell operating at the maximum power point (MPP), open circuit (OC), and short circuit (SC) bias points. This is achieved through a closed-loop frequency response system, calibrated to encompass illumiance levels ranging from 50 to 500 lux. The procedure for estimating the AC response of the PV cell is outlined, and the outcomes are subsequently employed in an analytical parameter extraction methodology. Experimental results from a 20 x 40 mm PV cell reveal that MPP represents the least favorable bias point in terms of bandwidth, whereas the SC bias point exhibits the most favorable performance. This observation validates the hypothesis that the optimal bias point for energy harvesting in PV cells is the worst bias point for communication purposes.

Index Terms— PV cell; Modeling; VLC.

I. INTRODUCTION

Light is a commonly used ambient energy source for energy harvesting. Besides being renewable energy, light is abundant in nature and has a very high power density (on the order of 10 $\mu$W/cm$^2$ indoors and 100 $\mu$W/cm$^2$ outdoors [1, 2]). Photovoltaic (PV) cells are common transducers used to harvest electrical energy from light, including natural sunlight, lasers, light-emitting diodes (LEDs), and other types of lamps.

Despite the widespread use of solar cells to harness light outdoors, there has recently been a growing interest in using PV cells to harness light indoors to power electronic Internet of Things (IoT) devices [3]. In addition, PV cells are also suitable as receivers for visible light communication (VLC), which uses visible light to transmit data. This is a very cost-effective wireless method of data transmission because it can share existing lighting infrastructure. It also has advantages in terms of security, as the light signal does not penetrate walls, limiting the reception area. In this context, the light is modulated by an LED through small changes in illuminance and detected by a photovoltaic cell in the form of voltage or current fluctuations. Other advantages of VLC are its insensitivity to electromagnetic interference and the availability of a large and unregulated band worldwide [4]. A disadvantage is the communication limiting factor caused by noise, especially in VLC systems that often rely on non-coherent signal detection. In addition, achieving low noise in a receiver circuit usually comes at the cost of increased power consumption [4]. Another limitation is the low bandwidth offered by a PV cell.

The VLC opens up the possibility of developing new applications for IoT, such as smart agriculture, smart cities, underwater communications, biomedical devices, and others, which has recently led to the introduction of a number of commercial off-the-shelf products that use this technology [5].

In recent years, the trade-off between energy harvesting and data communications has been explored. In the work of [6], an AC-DC separation receiver capable of transmitting lightwave information and energy simultaneously at a data rate of 784 Mb/s and a harvested power of 1 mW using a gallium arsenide (GaAs) vertical-cavity surface emitting laser (VCSEL) was developed. In another work, the feasibility of a communication link with a data rate of 11.84 Mbps with a bit error rate (BER) of 1.6 · $10^{-3}$ was demonstrated for a received optical signal with a peak-to-peak amplitude swing of 4780 lux [7].

A good PV cell electrical model is important for the development and simulation of a VLC system, both in DC and AC. Moreover, accurate extraction of model parameters is essential for proper estimation of generated voltage and current as a function of incident light intensity. The most typical electrical model of a PV cell is the 1D2R, which consists of a diode and two resistors. There are several studies presenting different evaluation methods to extract and estimate the DC parameters of this model [8, 9, 10], but little is said about the equivalent small-signal AC model, which is of great interest for communication applications.

In this paper, we present a technique for measuring and modeling the small-signal parameters of a PV cell in different bias regions using a closed-loop frequency response system. It is calibrated for low illuminance levels and thus provides an accurate model of the PV cell bandwidth for indoor communication purposes. A setup for measuring the PV cell AC response is described and the results are applied.
to an analytical parameter extraction procedure. In our analysis, we assume that the PV cell has a constant temperature since the goal is to model it for indoor use. However, temperature variations affect both DC and AC behavior and should be considered for outdoor applications, as discussed in [11].

The main contribution of this work is the description of an analytical procedure for parameter extraction of the PV cell small signal model under different illuminance and bias conditions.

This paper is organized as follows: Section II presents the DC and AC PV cell electrical models; Section III describes the measurement setup used to acquire the I-V characteristic of the PV cell and its frequency response; Section IV details the parameter extraction procedure; Section V discusses the biasing of the PV cell for communication purposes; finally, Section VI summarizes the conclusions.

II. PV CELL ELECTRICAL MODEL

The prevalent static electrical model for photovoltaic (PV) cells is referred to as the 1D2R model. It encompasses a diode alongside two resistors, as depicted in Figure 1 [12]. This specific electrical model presents the best trade-off between parameter count and accuracy [13]. The resulting output current, denoted as \( I_{out} \), can be determined through circuit analysis, as follows:

\[
I_{out} = I_{pv} - I_s \left( e^{\frac{V_{out_pv} + R_s I_{out}}{nV_{t}}} - 1 \right) - \frac{V_{out_pv} + R_s I_{out}}{R_{sh}}
\]

(1)

There are five model parameters that depend on the PV cell fabrication process. \( I_{pv} \) is the equivalent current source modeling the current generated by the photovoltaic effect, \( I_s \) is the diode saturation current, \( n \) is the diode ideality factor, \( R_s \) is the PV cell series resistance and \( R_{sh} \) is the PV cell shunt resistance. There is also a dependence of temperature \( T \), modeled by the thermal voltage \( V_t = kT / q \), in which \( q \) is the electron charge and \( k \) is the Boltzmann constant. The current \( I \) is implicit in Eq. 1, so it is necessary to implement a numerical solver to estimate it as a function of the output voltage \( V \) and free parameters.

Consider that the PV cell is biased in DC and a small AC component \( i_{pv} \) is applied representing a received signal. If \( i_{pv} << I_{pv} \), diode \( D_1 \) can be replaced by its dynamic model, which comprises a dynamic resistance \( r_d \) in parallel with an equivalent capacitance \( C_{eq} \), as shown in Fig. 2 [14] [15]. The equivalent capacitance is a parallel association of diffusion capacitance \( C_d \) and junction capacitance \( C_j \) that determines the dynamic properties of the PV cell [16]. The diffusion capacitance \( C_d \) occurs due to stored charge of minority electrons and minority holes near the depletion region. \( C_d \) is thus proportional to the minority carrier lifetime. The junction capacitance \( C_j \) in forward-biased p-n junction is dependent on doping concentration, material and geometry properties. Both capacitances are non-linear with respect to the bias voltage, which results in a variation for different illuminance levels and output loads.

III. MEASUREMENT SETUP

To obtain a real estimate of the bandwidth of a PV cell for communication purposes in an indoor environment, we performed a series of electrical measurements for DC and AC characterization. The target is a 20 x 40 mm polycrystalline Si cell illuminated by an array of conventional white LEDs. The illuminance is between 50 and 500 lux, which corresponds to a typical illuminance in an office room with artificial light. The following subsections detail the measurement setups for DC and AC characterization.

A. Measurement of the I-V Characteristic Curve

To obtain real data for parameter extraction, I-V measurements were performed on a compact 20x40 mm crystalline silicon photovoltaic (PV) cell. Illumination was provided by a cold LED lamp, more specifically a 50 W MTX mini floodlight model, and tests were conducted during nighttime to mitigate any interference from natural light. The ambient temperature during the measurements was about 24°C. The measurement arrangement is depicted in Figure 3, which shows the block diagram of the whole setup. The output of the PV cell was connected to a B1500A semiconductor parameter analyzer, which acted as a voltage source that could be varied from 0 to 1 V with a step of 0.6 mV. This setup effectively simulated a variable load resistance \( (R_L) \) ranging from 0 to infinity. To measure illuminance, an Instrutherm LD-550 luxmeter was strategically positioned near the target PV cell. The configuration of the actual experimental setup is shown in Figure 4.

The I-V characteristics were obtained for different illuminances between 50 and 500 lux. The illuminances were ob-

![Image](image-url)
tained by placing the light source at different distances from the PV cell.

B. Measurement of the AC Response

The configuration for performing measurements is illustrated by the block diagram shown in Fig. 5. For this purpose, the low-frequency transfer function module LF3L5 of the Agilent E5061B network analyzer is used to generate a frequency sweep signal and to measure the AC transfer function of the proposed characterization system. The generated AC signal is amplified and combined with a DC level to finally drive an array of LEDs. This amplification is performed by the amplifier shown in Figure 6. By varying the resistor $R_B$, the DC collector current of the transistor can be adjusted directly proportional to the DC base current ($I_b$), thus controlling the light intensity emitted by the LEDs. The PV cell is located a short distance of 45 cm from the LED array in an enclosed compartment, ensuring that the illuminance cannot be affected by external fluctuations. Next to the PV cell is a digital luxmeter (model MLM-1020), employed to measure the illuminance. To obtain a comprehensive evaluation, the output voltage generated by the PV cell is connected back to the network analyzer, creating a closed loop that allows the system gain to be measured. By sweeping the frequency of the input AC signal, the overall AC response of the solar cell can be measured. By changing the load resistance $R_L$, the PV cell can be biased across different operating conditions. A visual representation of the implemented measurement setup can be found in Fig. 7.

The AC response obtained from the measurements can be seen in Fig. 8 for three different operating conditions: maximum power point (MPP), open circuit (OC) and short circuit (SC). The input AC power was configured at -30 dBm, with the ambient temperature held constant at $24^\circ$C. The illuminance incident on the PV cell ranged from 50 lux to 500 lux, encompassing the entire range of interest. All plots show normalized voltage gain, with the -3 dB frequencies (cutoff frequencies) indicated by blue markers. The graphs of cutoff frequencies versus illuminance is shown in Figure 9. It can be seen that $f_c$ exhibits a linear increase with illuminance, albeit at different rates depending on the operating point of the PV cell. The narrowest bandwidth is observed at MPP, where $f_c$ ranges from 880 Hz to 2.8 kHz and increases at a rate of 4.4 Hz/lux. Meanwhile, in OC, the cutoff frequency increases at a rate of 8.8 Hz/lux, whereas in SC it increases even faster to 20.9 Hz/lux. This leads to a $f_c$ peak of 10.8 kHz at 500 lux in the SC scenario.

It is not practical to measure the AC characteristics of a PV cell for all illuminances. Therefore, translation equations are required to scale the characteristic points of the cell as a function of illuminance $G$ [17]. Three measured points were selected (50, 250, and 500, in Fig. 10 in orange) and the translation functions (in blue) were estimated by a curve fitting procedure, resulting in the following expressions:
Fig. 8: Measurement results for the closed loop gain of a 20 x 40 mm PV cell biased in 3 different points: a) MPP; b) open circuit; c) short circuit.

Fig. 9: Measurements of cutoff frequency in function of illuminance for three different bias conditions.

Mathematical expressions for the cutoff frequencies are:

\[ f_{c}(MPP) = 4.3662 \cdot G + 661.3750 \]  
\[ f_{c}(OC) = 8.7315 \cdot G + 349.7316 \]  
\[ f_{c}(SC) = 20.8752 \cdot G + 271.7869 \]  

With these expressions, it is possible to estimate the cutoff frequency for all intermediate points in the range of interest.

Looking at the behavior of the cutoff frequency as a function of PV cell load, we can see that it is not linear. Fig. 11 shows the measurement results for the cutoff frequency as a function of the output voltage generated by the PV cell illuminated at 200 and 300 lux. A high output voltage means operation close to open circuit, while a low output voltage refers to the operation close to short circuit. It can be seen that there is a point of minimum bandwidth between 0.15 and 0.20 V, which match with the maximum power point. This result confirms the hypothesis that the best bias point of the PV cell for energy harvesting is the worst bias point for visual light communication.

If we consider the PV cell has to simultaneously perform VLC and power transfer, it is possible to define a figure of merit combining both performance parameters as:

\[ FoM = f_{c} \cdot P_{\text{out}} \]  

Here \( P_{\text{out}} \) is the power delivered by the PV cell at its output. Relating the FoM to \( V_{\text{out}} \), the results can be seen in Fig. 12. The higher FoM is located a few mV from the short-circuit bias point and decreases slightly up to MPP. While the maximum bandwidth is achieved under short-circuit condition, the energy harvest at this point is negligible due to the extremely low DC voltage. Therefore, biasing the PV cell at MPP can be a good choice to compromise between delivered power and bandwidth. When \( V_{\text{out}} \) is biased higher than MPP, the FoM decreases sharply, and this region must be avoided in both cases. The open circuit point leads to the worst FoM.

IV. PARAMETER EXTRACTION PROCEDURE

Based on the obtained measurements, it is possible to extract the AC parameters of the PV cell small-signal electrical model shown in Fig. 2. To do this, we first need to extract the DC parameters for the 1D2R PV cell model. We implemented the extraction method described in [18] considering the same illuminances used in the AC measurements and extracted the values of \( n, I_{S}, I_{PV}, R_{S}, \) and \( R_{SH} \) that model the equivalent circuit of Fig. 1.

A. DC Parameters

Six significant characteristic points can be discerned and extracted from the plotted curves. One of them, the open circuit voltage \( (V_{oc}) \), is determined at the points where \( I = 0 \), as shown in Figure 13a. The short-circuit current \( (I_{sc}) \) can be
Fig. 10: Translated cutoff frequency x Illuminance. a) In MPP; b) Open circuit; c) Short circuit. Red dots represent the measured points, and the highlighted dots are the points used to determine the translation function.

estimated by examining the I-V characteristic curves at the points where \( V = 0 \). Additionally, two parameters, namely the reciprocals of the slopes at the open-circuit and short-circuit points, are denoted as \( R_{s0} \) and \( R_{sh0} \), respectively. These values are calculated according to the following expressions:

\[
R_{s0} = -\frac{dV}{dI}\bigg|_{V=V_{oc}}
\]

\[
R_{sh0} = -\frac{dV}{dI}\bigg|_{I=I_{sc}}
\]

For calculating the slope of \( 1/R_{sh0} \) we used the first 100 points of the curves of Fig. 13a, which corresponds to a \( \Delta V \) of 60 mV. For calculating \( 1/R_{s0} \) we used the last 15 points of the curves, which results in a \( \Delta V \) of 9 mV. These values were empirically estimated in order to minimize numerical errors, since the derivative of the first and last points of the curves suffer from numerical noise.

The maximum power point can be seen from the power-voltage curves (Fig. 13b). At these points it is possible to estimate the voltage \( V_{mp} \) and current \( I_{mp} \) that extract the maximum power from the PV cell.

From these 6 measured characteristic points it is possible to calculate the 5 parameters of the 1D2R PV cell model using the following procedure [18].

The shunt resistance is estimated to be equal to \( R_{sh0} \):

\[
R_{sh} = R_{sh0}
\]

The value of \( n \) can be extracted from the maximum power point as:

\[
n = \frac{V_{mp} + I_{mp}R_{s0} - V_{oc}}{I_{mp}} \left( \ln(I_{sc} - \frac{V_{mp}}{R_{sh}} - I_{mp}) - \ln(I_{sc} - \frac{V_{oc}}{R_{sh}}) + \frac{I_{mp}}{I_{sc} - \frac{V_{oc}}{R_{sh}}} \right)
\]

The diode saturation current \( I_s \) can be defined as:
Iscing static parameters:

Measurements as a function of frequency shown in Fig. 8 [19].

The dynamic resistance can be estimated from the following static parameters:

\[ r_d = \frac{n \cdot V_t}{I_{pv}} \]  \hspace{1cm} (13)

This dependence results in a variation of \( r_d \) with illuminance, reducing the value as the illuminance increases. The effective minority carrier lifetime \( \tau \) is given by:

\[ \tau = r_d \cdot C_{eq} \]  \hspace{1cm} (14)

The small-signal model reveals a single-pole circuit whose equivalent resistance \( r_0 \) can be estimated as:

\[ r_0 = \frac{1}{\frac{1}{r_d} + \frac{1}{R_{sh}} + \frac{1}{R_s + R_L}} \]  \hspace{1cm} (15)

It can be related to an equivalent first-order lowpass filter whose -3 dB cutoff frequency \( f_c \) is given as:

\[ f_c = \frac{1}{2\pi r_0 C_{eq}} \]  \hspace{1cm} (16)

So, the diode equivalent capacitance can be estimated as follows:

\[ C_{eq} = \frac{1}{2\pi f_c r_0} \]  \hspace{1cm} (17)

Resistance \( r_d \) is in the same order of magnitude than \( R_s \) and is much lower than \( R_{sh} \). It can be seen that the pole location is dependent on the load \( R_L \) applied to the PV cell. In open circuit (very high \( R_L \), the equivalent output resistance approaches the value of \( r_d \). On the other side, if the PV cell is operating in short circuit (very small \( R_L \), \( r_0 \) approaches \( r_d || R_s \).

The bandwidth is subject to variations influenced by temperature and injection level, as it is intrinsically governed by the minority carriers lifetime \( (\tau) \). As stated in [14], due to the correlation between the efficiency of a solar cell (with regards to energy harvesting) and the lifetime of the minority carriers, achieving a photoreceiver with elevated bandwidth cannot be anticipated when employing a highly efficient PV cell operating at the maximum power point (MPP).

Knowing the values of \( n \) and \( I_{PV} \) we extract the diode dynamic resistance \( r_d \) using eq. 13. For the three bias regions (MPP, OC and SC), and for illuminances ranging from 50 to 500 lux, the equivalent output resistance \( r_0 \) is calculated by eq. 15 using the DC parameters \( R_s \) and \( R_{sh} \). With the measured values of \( f_c \), the value of the diode equivalent capacitance \( C_{eq} \) can be estimated using eq. 16. The extracted AC parameters are summarized in Tab. II. The load resistance \( R_L \) was adjusted to bias the PV cell in MPP for the maximum delivered power scenario. For open circuit, \( R_L \) was fixed in 100 MΩ. For emulating the SC scenario, \( R_L \) was set to the minimum value that approached \( V_{out} \) to zero (although not achieving exactly 0 V due to limitations in the measurement equipment).

The graphs in Fig. 14 show the estimated values of \( r_d \), \( r_0 \), and \( C_{eq} \) as a function of illuminance for the three bias regions of interest. It is clear that the resistances decrease with increasing illuminance in all cases. Since the cutoff
Table I: Extracted DC 1D2R model parameters for different illuminance levels.

<table>
<thead>
<tr>
<th>Illuminance (lux)</th>
<th>$I_{pv}$ (mA)</th>
<th>$I_s$ ($\mu$A)</th>
<th>$n$</th>
<th>$R_e$ (Ω)</th>
<th>$R_{sh}$ (kΩ)</th>
<th>RMSE (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.0708</td>
<td>0.0748</td>
<td>1.0382</td>
<td>373.6491</td>
<td>6.9897</td>
<td>0.0014</td>
</tr>
<tr>
<td>100</td>
<td>0.1202</td>
<td>0.2164</td>
<td>1.3123</td>
<td>195.5369</td>
<td>6.5076</td>
<td>0.0014</td>
</tr>
<tr>
<td>150.4</td>
<td>0.1620</td>
<td>0.4592</td>
<td>1.5107</td>
<td>98.9600</td>
<td>4.6656</td>
<td>0.0022</td>
</tr>
<tr>
<td>200</td>
<td>0.2206</td>
<td>0.4778</td>
<td>1.5770</td>
<td>82.9531</td>
<td>4.8232</td>
<td>0.0021</td>
</tr>
<tr>
<td>250</td>
<td>0.2624</td>
<td>0.6964</td>
<td>1.6907</td>
<td>57.9388</td>
<td>3.6991</td>
<td>0.0026</td>
</tr>
<tr>
<td>300</td>
<td>0.3320</td>
<td>0.7688</td>
<td>1.7078</td>
<td>57.2898</td>
<td>4.2135</td>
<td>0.0021</td>
</tr>
<tr>
<td>350</td>
<td>0.3623</td>
<td>0.8929</td>
<td>1.7611</td>
<td>57.9515</td>
<td>3.6991</td>
<td>0.0026</td>
</tr>
<tr>
<td>400</td>
<td>0.4429</td>
<td>0.8858</td>
<td>1.8078</td>
<td>41.2964</td>
<td>3.8660</td>
<td>0.0021</td>
</tr>
<tr>
<td>500</td>
<td>0.5622</td>
<td>0.8758</td>
<td>1.8282</td>
<td>32.1803</td>
<td>3.1983</td>
<td>0.0021</td>
</tr>
</tbody>
</table>

frequency increases linearly with illuminance, and it is related to $r_0$ as defined in eq. 16, the equivalent resistance $r_0$ decreases proportionally to $1/G$. This behavior is confirmed with the extracted parameters. The equivalent capacitance, on the other hand, behaves differently in the MPP than in the OC and SC regions, but with a smaller variation as a function of illuminance.

To evaluate the quality of the extracted parameters with respect to the measurement results, we simulated the PV cell closed loop response, as shown in Fig. 15. It is possible to notice the good fitting between analytical and measurement results, demonstrating that the proposed parameter extraction procedure is adequate for simulating the device for communications.

V. PV CELL BIASING FOR COMMUNICATION

As shown before, the near-SC region presents the best FoM for simultaneous use of the PV cell for generating power and for communications purposes. However, operating close to the SC region makes the voltage signal to be very small, reducing the signal to noise ratio (SNR) of the communication signal. Thus, at SC operation it is interesting to use the output AC current signal instead the output AC voltage signal. In this case, a transimpedance amplifier (TIA) should be employed to convert the AC current level in a reasonable voltage level.

Any signal voltage developed across the PV cell reacts with the internal P-N junction capacitance, shunting the output current at higher frequencies. Reducing the effects of the voltage across the PV cell capacitance greatly improves bandwidth. This can be achieved by isolating the signal voltage from the PV cell using a current-to-voltage converter [20]. The circuit depicted in Fig. 16 implements this function. It is a transimpedance amplifier (TIA), an active converter that transforms input current to a corresponding output voltage. This configuration represents a simple inverting amplifier with negative feedback. A feedback resistor, $R_f$, connects the output to the inverting terminal of the amplifier. The virtual ground at the input of the operational amplifier forces the PV cell to operate near the short-circuit bias point.

We have implemented this circuit using an AD823AN operational amplifier with $R_f$ equal to 8.18 kΩ. Its high input impedance makes the input current practically negligible. Consequently, all the current generated by the PV cell flows through $R_f$. Challenges arise from the input of the operational amplifier, which introduces an inherent parasitic
capacitance that results in an undesirable second pole location and consequently a poor phase margin. To mitigate this instability, the solution is to introduce a feedback capacitor $C_f$ (1013 pF in our implementation) that operates in parallel with $R_f$ to compensate this pole. The bandwidth of the whole circuit thus depends mostly on the value of $C_f$ and $R_f$, and only to a very small extent on the internal capacitance of the PV cell.

Fig. 15 shows the measured frequency response of the PV cell connected to the TIA for illuminances from 50 to 250 lux. It can be seen that the voltage gain remains relatively constant as the illuminance changes from DC to 30 kHz. In Fig. 17b the phase response is shown. At low frequencies, minimal phase variations can be seen as the illuminance changes. On the other hand, significant variations can be noticed at higher frequencies. Driving the PV cell with a TIA at a low illuminance of only 50 lux increased $f_c$ by approximately $20\times$, whereas at 500 lux $f_c$ increased roughly $3\times$. Therefore, this approach is essential for a wider bandwidth VLC system for indoor use.

This simple TIA produces a significant offset for higher gain applications. Alternatives are to replace the $R_f$ resistor with a tee-network or with a DC offset cancellation loop, as demonstrated in [21].

The measurement results confirm the bandwidth improvement by the TIA circuit, which is important for the adoption of PV cells as receivers in VLC systems.
Table II. Extracted AC PV cell model parameters for different illuminance levels in three bias conditions.

<table>
<thead>
<tr>
<th>Bias</th>
<th>Illum. (lux)</th>
<th>$r_v$ (Ω)</th>
<th>$R_L$ (Ω)</th>
<th>$R_{sh}$ (Ω)</th>
<th>$R_{eq}$ (nF)</th>
<th>$\tau$ (µs)</th>
<th>$f_c$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPP</td>
<td>50</td>
<td>378.98</td>
<td>373.65</td>
<td>6998.75</td>
<td>2402.59</td>
<td>318.28</td>
<td>568.44</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>282.24</td>
<td>195.54</td>
<td>6507.59</td>
<td>1602.10</td>
<td>235.13</td>
<td>526.71</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>241.06</td>
<td>98.96</td>
<td>4665.63</td>
<td>1276.12</td>
<td>196.47</td>
<td>587.57</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>184.78</td>
<td>82.95</td>
<td>4823.15</td>
<td>1011.15</td>
<td>153.06</td>
<td>593.17</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>166.58</td>
<td>57.94</td>
<td>4366.81</td>
<td>893.03</td>
<td>137.29</td>
<td>661.32</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>132.97</td>
<td>57.29</td>
<td>4213.48</td>
<td>744.79</td>
<td>111.05</td>
<td>654.53</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>125.67</td>
<td>65.95</td>
<td>3699.14</td>
<td>695.41</td>
<td>104.81</td>
<td>683.76</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>105.52</td>
<td>41.30</td>
<td>3865.98</td>
<td>594.82</td>
<td>84.44</td>
<td>747.38</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>84.07</td>
<td>32.18</td>
<td>3198.29</td>
<td>488.15</td>
<td>70.78</td>
<td>790.53</td>
</tr>
</tbody>
</table>

| OC   | 50           | 378.98     | 373.65    | 6998.75      | 824.86       | 276.54     | 382.80      | 105.86      | 1.50         |
|      | 100          | 282.24     | 195.54    | 6507.59      | 458.88       | 191.40     | 289.17      | 55.35       | 2.88         |
|      | 150          | 241.06     | 98.96     | 4665.63      | 337.11       | 150.24     | 289.80      | 43.54       | 3.66         |
|      | 200          | 184.78     | 82.95     | 4823.15      | 241.90       | 114.97     | 314.33      | 36.14       | 4.40         |
|      | 250          | 166.58     | 57.94     | 4366.81      | 201.92       | 99.20      | 311.38      | 30.89       | 5.15         |
|      | 300          | 132.97     | 57.29     | 4213.48      | 158.31       | 80.67      | 306.78      | 24.75       | 6.43         |
|      | 350          | 125.67     | 65.95     | 3699.14      | 146.00       | 77.25      | 285.73      | 22.07       | 7.21         |
|      | 400          | 105.52     | 41.30     | 3865.98      | 117.62       | 62.39      | 316.77      | 19.76       | 8.05         |
|      | 500          | 84.07      | 32.18     | 3198.29      | 92.46        | 49.43      | 296.47      | 14.66       | 10.86        |

VI. Conclusion

This paper provides a comprehensive characterization of a 20 x 40 mm photovoltaic (PV) cell intended for utilization as a receiver within a Visible Light Communication (VLC) system. The AC small signal parameters were extracted for three distinct bias points: maximum power point, open circuit, and short circuit. The considered illuminance levels ranged from 50 lux to 500 lux, aligning with the usual conditions found in indoor settings illuminated by artificial light.

The obtained results unveil that the PV cell cutoff frequency escalates with increasing illuminance levels, and this trend depends on the specific bias point of the cell. It is noteworthy that the optimal bias point for communication tasks aligns with the short circuit, while the opposite is true for maximum power point (MPP). This characteristic, which contradicts the energy harvesting ideal bias point (MPP), underscores the presence of a trade-off between communication bandwidth and energy harvesting efficiency.

Using a TIA to bias the PV cell output in short circuit and to cancel the effect of internal capacitance is a good alternative to improve the bandwidth, allowing the use of the PV cell as a receiver in a visual light communication system.

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References


