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Outdoor PL Imaging of Photovoltaic Modules at Constant Operating Point

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Recent years have seen a dramatic increase in utility scale solar deployment [1] driven by cost reductions in installations [2]. Photoluminescence (PL) imaging is a powerful inspection technique for semiconductors wafers and devices [3] that has found widespread application in research and industry. However, it was previously limited to laboratory applications [4, 5]. Recently, the inspection of field-deployed solar modules under full sunlight condition was reported [6, 7]. Yet a significant complication of outdoor PL imaging is the need to switch between two different operating points which requires making electrical contact to the module terminals [6], or an optical modulator placed in front of the module [7]. In the current study we present an outdoor PL imaging method that is applied to modules at constant operating point. Besides being easier to implement in practice, this method is expected to yield higher throughput and be applicable to a broader range of system configurations.

Background and Experimental Setup

The system consists of a computer controlled InGaAs camera with suitable filtering [Fig. 1(a)]. The module under test is illuminated by sunlight, which is the sole source of excitation. The PL signal is typically about two orders of magnitudes weaker than the sunlight that is reflected from the module. Hence, removing the sunlight contribution is critical to obtain a high-quality PL image. In previously reported method, the luminescence image is obtained by subtracting an image under high current extraction [typically short circuit (J_{sc}) or maximum power point condition], which contains barely any PL signal as most of the photogenerated carriers are extracted; from an image taken under lower extraction for which the PL is increased whereas the sunlight intensity remains unchanged. In the following, J_{sc} and open-circuit voltage (V_{oc}) conditions are used as the high and low extraction conditions, respectively. This corresponds to the maximum PL difference accessible without an external electrical source. For this experimental proof of concept, a high-performance interdigitated back contact minimodule with intentionally induced cracks is used.

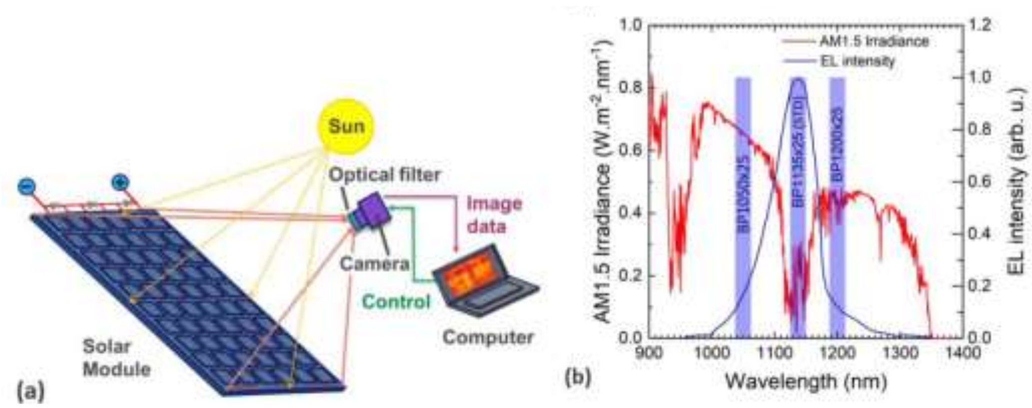


Fig. 1 (a) Set-up used to perform outdoor PL imaging with the multi-filter method. (b) AM1.5 solar spectrum, typical room temperature luminescence spectrum of crystalline Si and the used band pass filters.

Rather than changing the module's operation point, the method proposed here relies on changing the optical filtering in front of the camera between three different infrared (IR) bandpass filters, each with approximately 25 nm bandwidth as shown in Fig. 1(b):

(1) Standard outdoor PL filter with 1135 nm centre wavelength (CW)
(2) Blue-shifted filter with 1050 nm CW
(3) Red-shifted filter with 1200 nm CW

The bandpass filters are selected such that (1) the standard filter measures at the peak intensity of the silicon PL emission, which also coincides with an atmospheric water vapour absorption band as seen in Fig. 1(b). Both factors maximise the ratio between the PL and ambient light for filter (1). The blue- (2) and red-shifted (3) filters are chosen with CWs as close as possible to the standard filter, but far enough such that there is only a very weak PL signal contained in the measured signal, while the sunlight signal is significantly increased. In this fashion, the reflectance signal from the sunlight measured with filters (2) and (3) is very similar to the one measured with the standard filter (except from a scaling factor) but contains almost no PL. The two images obtained with (2) and (3) are thus, almost pure optical reflection images, while the image obtained with (1) is a mixture of optical reflection and PL signal.

Constant operating point PL imaging and comparison with dual operating point imaging

For comparison, the standard method for outdoor PL imaging [9] is applied by switching the module between V_{oc} and J_{sc}, and images are taken for both operating points and each filter (Fig. 2.) The J_{sc} image (centre) is subtracted from the V_{oc} image (left) to obtain the PL image (right).

Filter (1) (1135 nm), optimised to maximise the PL over sunlight ratio, shows the best PL image quality. For filter (2) (1050 nm), the PL fraction contained in the Voc image drops significantly compared to filter (1), as a result, only extended defects can be identified. While for filter (3) (1200 nm), no significant signal could be detected in the subtraction image, which shows that filter (3) image contains reflected light only and no significant PL signal.

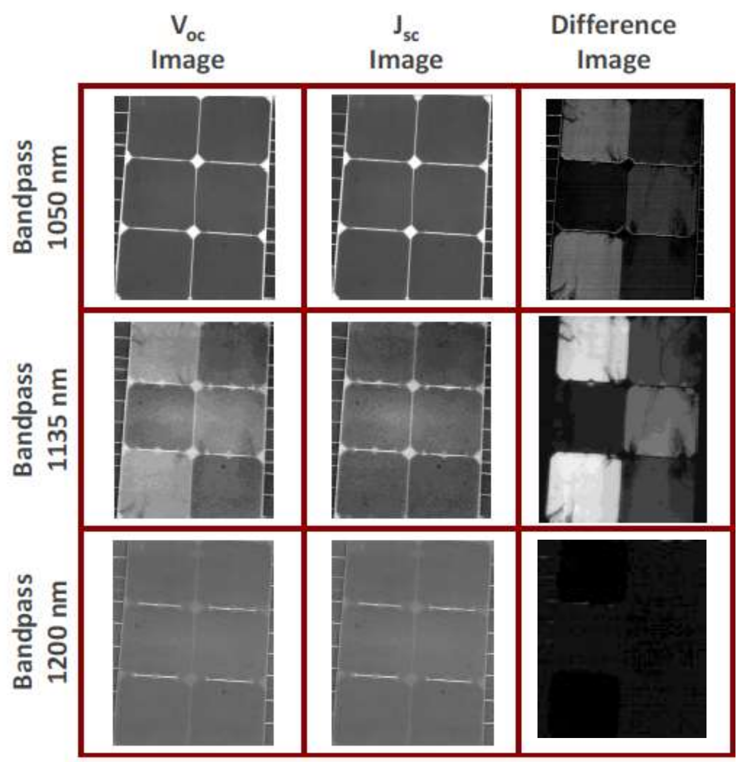


Fig. 2 Outdoor images taken for all three bandpass filters at V_{oc} and J_{sc} conditions. The third column displays the calculated difference image (PL).

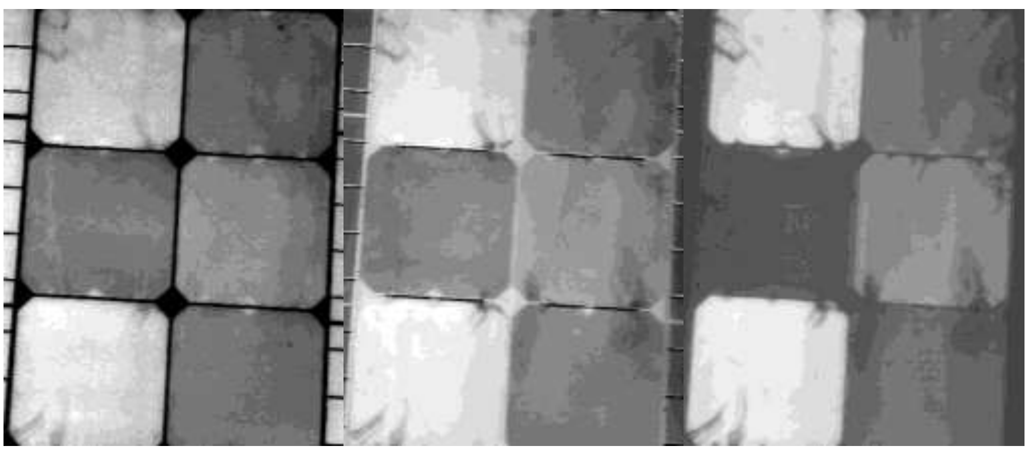
In the following, a method to obtain PL image solely based on the images taken under V_{oc} is described and compared to the previous method. As the image taken with filter (1) contains significantly higher PL signal to total signal fraction, this image is used to provide the PL information, whereas images taken with filters (2) or (3) are used to remove the sunlight reflection. While images taken with the same filter at V_{oc} and J_{sc} have the same sunlight signal, images taken at V_{oc} but with different filters have different sunlight signals because of the rapidly changing sunlight spectral intensity between the three filters (Fig. 1b). As a consequence, a simple image subtraction is ineffective to retrieve the PL image.

However, a PL image can be obtained using a scaling procedure. Here we used the normalised image division to consistently retrieve the PL image information:

(1) The image obtained with filter (1) is divided by either of the images obtained with filters (2 or 3).
(2) The resulting ratio image is normalised such that the average over the cell area is unity.
(3) The grey scale is adjusted to display value in the range [0.75 to 1.05~1.10].

A direct comparison between the standard approach, using module switching and the proposed method using only V_{oc} images is shown in Fig. 3. Combining two images taken with filters (1) and (3) gives better results than combining images taken with filters (1) and (2). This is attributed to the absence of significant PL signal when using filter (3).

Notwithstanding, a slightly lower image quality compared to the standard approach, the constant operating point outdoor PL imaging allows to accurately detect and identify electronic defects such as cracks. Furthermore, this method is significantly easier to perform in practice since one only requires changing the optical filter in front of the camera lens, rather than requiring switching of the module's operating point. No access to the module itself is thus requires, which simplifies outdoor PL imaging and may be more suited to implementation in unmanned aerial vehicles compared to the standard method. We expect this method to be particularly suited to high efficiency modules where the ratio of PL signal to ambient reflected signal is comparatively large.



1135(V_{oc}) / 1050(V_{oc}) **1135(V_{oc}) / 1200(V_{oc})** **1135(V_{oc}) – 1135(J_{sc})**

Fig. 3 Comparison of outdoor PL imaging with the proposed 2-filter method (left and centre) at constant operating point (V_{oc}) and standard approach using switching between V_{oc} and J_{sc} (right).

Conclusion

In this study we presented a method that enables taking PL images of modules in full sunlight, without the need for switching the module's operating point. This is achieved via taking module images in two different infrared spectral bands. The resulting PL image is comparable in quality to the image obtained with the more established method based on module switching.

Reference

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