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Novel Photovoltaic Micro Crack Detection Technique

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Abstract— **This paper presents a novel detection technique for inspecting solar cells micro cracks. Initially, the solar cell is captured using Electroluminescence (EL) method, then processed by the proposed technique. The technique consist of three stages, the first stage combines two images, the first image is the crack-free (healthy) solar cell, whereas the second is the cracked solar cell image. Both output images processed into a bit-by-bit gridding technique, which enables the detection of all bits in the considered area of the cracked solar cell. The second stage uses an OR gate between each of the examined bits for both healthy and cracked solar cells. The final calibrated image presents a high quality, and low noise structure, thus easier to identify the micro crack size, location and its orientation. In order to examine the effectiveness of the proposed technique, three different cracked PV solar cells have been examined. The results show that the micro cracks size, orientation, and location is more visible using the proposed technique. In addition, the developed technique has been validated using a full scale PV module, and compared with up to date available PV micro crack detection methods.**

Index Terms*— *Photovoltaic; Solar cells; Micro cracks; Electroluminescence.

I. INTRODUCTION

Micro cracks in solar cells are a genuine problem for Photovoltaic (PV) modules. They are hard to avoid and, up to date, the impact of PV micro cracks on the performance of the PV modules in various environmental conditions has not been reported. In order to examine micro cracks in PV modules, several methods have been proposed. Resonance ultrasonic vibrations (RUV) technique for crack detection in PV silicon wafers has been developed by [1 and 2].

RUV technique uses ultrasonic vibrations of a tunable frequency and changeable amplitude are functional to the silicon wafer by an external piezoelectric transducer in a frequency range of 20 to 90 kHz. The transducer comprises a central hole allowing a reliable vacuum coupling between the wafer and transducer by applying 50-kPa negative pressure to the backside of the wafer. RUV PV micro crack technique is sensitive to crack length and its location, and can be used to reject or accept wafers. However, it does not identify the precise location of the PV crack.

Photoluminescence (PL) aiming technique was proposed to solve this problem, since it can be used to inspect micro cracks in silicon wafers and PV modules [3]. PL technique can be applied not only at the end of the PV solar cell's production, but also it can be slotted in during the process of production [4].

Y. Zhu et al. [5] proposed a new PL setup that enables inhomogeneous illumination with arbitrary illumination patterns to determine various parameters of solar cells. The results indicate that the use of inhomogeneous illumination significantly extends the range of photoluminescence imaging applications for the characterization of silicon wafers and solar cells.

Most recently, in 2018, the PL images are acquired using the sun as the sole illumination source by separating the weak luminescence signal from the much stronger ambient sunlight signal. This is done by using a suitable optical filtering and modulation of the PV cells biasing between the normal operating point and open circuit conditions [6].

Electroluminescence (EL) technique is another method for the micro crack detection in PV solar cells. EL technique is the form of luminescence in which electrons are excited into the conduction band through the use of electrical current by connecting the solar cell in forward bias mode. This technique is very attractive, because it can be used not only with small solar cell sizes but also, it can be used with full scale PV modules [7 and 8].

The EL method requires the solar cells to be in the forward bias condition in order to emit infrared radiation. The EL ranges from 950 to 1250 nm with the peak occurring at approximately 1150 nm. Emission intensity is dependent on the density of defects in the silicon, with fewer defects resulting in more emitted photons [9]. The EL system should be placed in a dark room, as the image of the cells is being taken by cooled CCD camera, we have already published the configuration and construction of the EL setup in [10].

M. Kontges et al. [11], investigated the impact of micro cracks on the performance of PV modules using EL imaging method. This research proves that micro cracks do not reduce the power generation of a PV module by more than 2.5%, if the crack does not harm the electrical contact between the cell and fragments.

Orientational distribution of micro cracks in crystalline PV cells was firstly presented by S. Kajari-Schröder et al. [12]. PV micro cracks were classified into six sub categories as follows: dendritic, several, $+45^0$, -45^0, Parallel to busbars, and Perpendicular to busbars. The analysis have been carried out using 27 PV modules using EL imaging technique, where the maximum micro cracks found in the PV modules is parallel to busbars with 50% relative occurrence.

Furthermore, I-V curve analysis based on gallium arsenide (GaAs) PV solar cell on silicon substrate for crack-free and cracked PV solar cells have been investigated by S. Oh et al. [13] using EL imaging technique. It was evident that the output voltage of the PV solar cells decreases while increasing the crack size.

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On the other hand, in 2018 a new micro crack detection method based on self-learning features and low-rank matrix recovery was proposed by X. Qian et al. [14]. First, the input image is preprocessed to suppress the noises and remove the busbars and fingers. Next, a self-learning feature extraction scheme in which the feature extraction patterns are changed along with the input image is introduced. Finally, the optimized result is further fine-tuned by morphological post processing.

In this paper, EL imaging technique was used to capture the micro cracks in PV solar cells. The EL detection technique is already shown in our previous articles [7 and 15]. Furthermore, the main contribution of this work is illustrated as follows:

- **Technique selection:** comparing various techniques to analyse the difference between crack-free and cracked solar cells.
- **Image resolution:** identifying the most suitable technique that has the optimum observable output image arrangement, in which it can be used to clearly identify the PV micro crack orientation, size, and location.
- **Evaluation:** the evaluation process is based on small scale solar cells and full scale PV module. A comparison between the proposed micro crack detection algorithm vs. an conventional EL imaging technique will be analysed.

This paper is organized as follows: section II explains the examined PV module and its electrical specifications. Section III and IV demonstrate various techniques for analyzing the PV micro crack images, and evaluating the final proposed detection technique. Finally, section V and VI draw relevant discussion and conclusion for the new offered micro crack detection technique respectively.

II. Tested PV Solar Cells

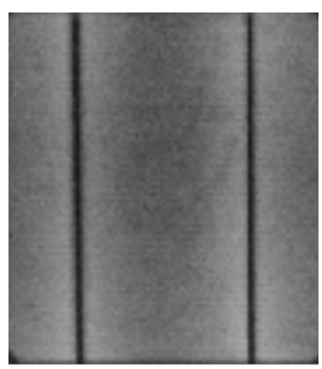
In this work, polycrystalline PV solar cells are inspected, a real image of the solar cell is shown in Fig. 1(a). Three total inspected cracked solar cells have been used. The examined solar cell has the following electrical parameters:

- Open circuit voltage (V_{oc}): 0.76 V.
- Short circuit current (I_{sc}): 8.42 A.
- Voltage at maximum power point (V_{mpp}): 0.64 V.
- Current at maximum power point (I_{mpp}): 7.86 A.
- Output power (W_p): 5.08 W.
- Cell Efficiency: 18.3%.

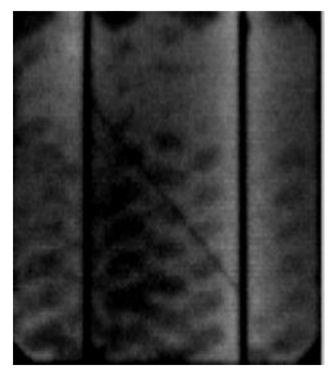
A healthy (crack-free) solar cell is shown in Fig. 1(b), and a cracked solar cell is shown in Fig. 1(c). Both crack-free and cracked solar cell images will be processed using various detection techniques, this will be explained in the next section (section III).

The electroluminescence system used to inspect the micro cracks is presented in Fig. 1(d). The system is comprised of a light-tight black-box where housed inside is a digital camera and a sample holder. The digital camera is equipped with a standard F-mount 18–55 mm lens. To allow for detection in the near infrared, the IR filter was removed and replaced with a full spectrum window of equal optical path length. In our setup, a Nikon D40 was used, but in principle any digital camera with similar grade CCD or CMOS sensor and where the IR filter can be removed would serve the purpose [16]. The bias was applied and the resultant current and the voltage are measured by a voltage and current sensors which are connected to the personal computer (PC).

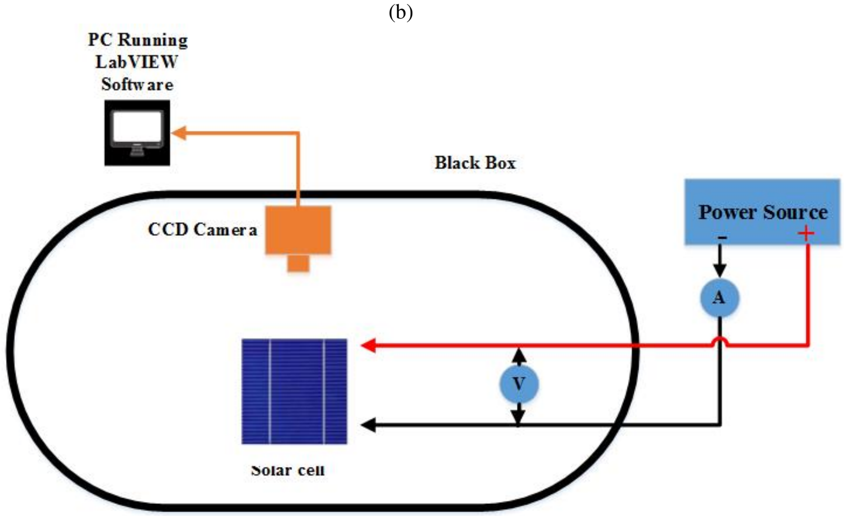
(a)



(b)



(c)



(d)

Fig. 1. (a) Ten Examined PV modules, (b) Healthy (crack-free) PV solar cell sample, (c) Cracked PV solar cell sample, (d) Electroluminescence experimental setup

III. PROPOSED MICRO CRACK DETECTION TECHNIQUE

This section describes the selection for the proposed EL detection technique. Fig. 2 shows the combination between the healthy and cracked PV solar cell. Six different techniques were used to combine both images, staring with "OR" gate, ending with the subtraction technique. The output image for each technique is also demonstrated in Fig. 2.

As can be noticed, the division technique has no output (fully black PV solar cell image), whereas the second worst output image when subtracting the healthy from the cracked image. However, the best image resolution for the crack image is identified using the OR gate (healthy solar cell image ORing with the cracked solar cell image). This result is obtained because the crack-free image would not add additional noise to the cracked solar cell image, though it cleans up the areas which have no presence of micro cracks.

In fact, each of the above listed techniques are based on a specific process which will calibrate bit-by-bit of the pixels for the captured solar cell images, thus to reduce the noise, and improve the quality of the output cracked solar cell image. The process for two bits is described in Fig. 3(a). As a result, the detection technique provides an enhancement in the solar cell EL image construction.

The OR combination can isolate the micro cracks form the inspected image due to two reasons. First, the ORing will subtract the original (healthy) solar cell image with the cracked solar cell image. Secondly, the ORing will restructure the image based on its resolution, therefore this combination would not be affected by the object sets/pixels. Whereas, compared to the subtraction method, if the number of pixels change, the difference between the healthy and cracked solar cell image would give wrong object identification, since the difference between the pixels is present.

Fig. 3(b) shows the output image of the cracked solar cell before and after the ORing bit-by-bit of the pixels for the image. As can be noticed, the output image contain limited source of noise and the filtration process for the noisy areas are clearly disappeared. This solar cell sample is referred as sample 1 in the manuscript.

In Fig. 3(b) two areas are present, the first area from the original image shows a widespread cracked area, in fact the image enhancement using the OR gate shows that few cracks only appear as a significant damage in the cell. Same comment applies for the second area shown in Fig. 3(b), where the original image show a crack, however, it does not perform that after the proposed detection technique applies. Therefore, it is evident that this area is a shadow that has been added by either the CCD camera or the noise of the communication link between the CCD and the PC, but as a final remark this is not a real damage in the solar cell which cannot be identified by the conventional EL imaging technique.

One of the biggest limitation in detecting cracks for PV solar cells that is required high cost equipment's such as high cost CCD cameras with high resolution, and a proper optical system which is normally hard to find as a commercial product. However, in this paper a low cost CCD camera with IR lens has been used. The output images due to the low cost camera show the cracked solar cell as a fully solid black area, which is in fact incorrect. Therefore, the proposed technique attempts to solve this problem.

Figs. 3(c) and 3(d) show two examples for the black area obtained by the EL imaging of cracked solar cell samples. This black area does not necessary corresponds to a crack in the solar cell, but additional noise is normally added by the camera, and the crack type, orientation, and size is hardly to find. After using the ORing method proposed in this article, the micro crack size and its orientation is clearly obtainable in the output calibrated image as shown in Figs. 3(c) and 3(d). The crack is more visible in both tested solar cell samples comparing to the conventional EL technique and that what we consider as a main contribution/impact of the presented micro crack detection technique.

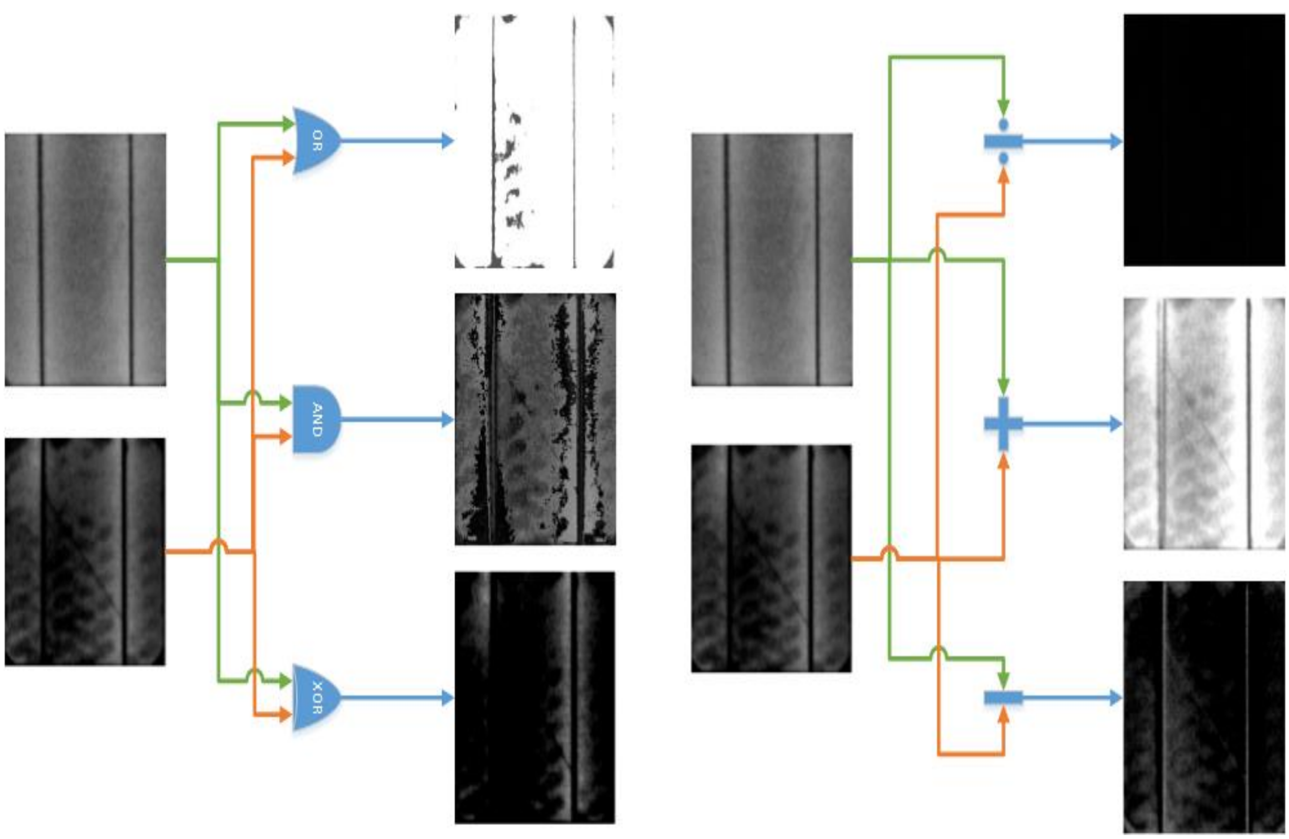


Fig. 2. The image of the healthy solar cell recombined with cracked solar cell using various techniques (OR, AND, XOR, Division, Addition, and Subtraction)

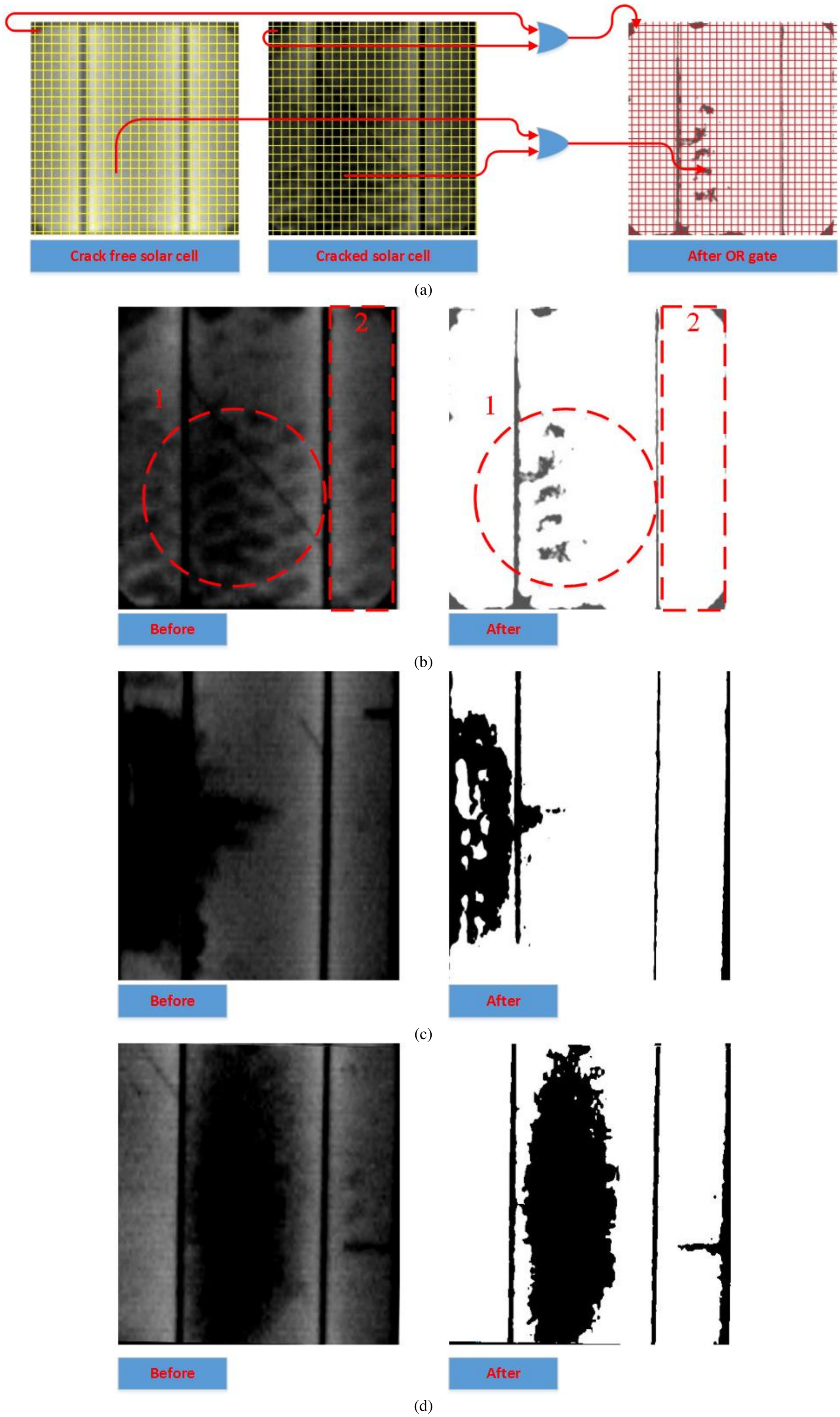


Fig. 3. (a) bit-by-bit pixel calibration ,(b) Before and after using the proposed OR gate method, this method uses the OR gate between each bit-by-bit of the pixels from the original cracked cell with free crack solar cell, this solar cell is corresponds to sample 1 in the entire manuscript, (c) Solar cell sample 2, (d) Solar cell sample 3

In order to draw a relevant summary of the entire micro crack detection and analysis procedure, Fig. 4 has been presented. This figure describes a brief summary of the detection, image calibration, and analysis of the observed data.

The first stage contains the EL imaging method for both crack free and the cracked solar cell, whereas the output image is proceeds into a bit-by-bit gridding (the output of this process is shown previously in Fig. 3(a)). The next stage processing an OR gate between each of the observed bit, thus enhancing the output image quality, and reducing the overall noise of the original EL image (the output of this process is shown previously in Fig.3 (a)).

Next, the bit-by-bit gridding will be removed from the output calibrated image. The final image has low noise, error, and the area of the crack is more visible compared to the original EL image (examples of the output images are shown in Figs. 3(c) and 3(d)). After the final calibrated image has been identified, it is possible to inspect the crack type, size, and its orientation.

In fact, the image calibration process stage requires the output images form the initial stage (EL imaging). The ORing technique will be applied for both inspected images, and the bit-by-bit gridding technique is also used. The final output image can be used either to identify the micro cracks size, location, and orientation, or it can be used to predict possible loss in the output power of the inspected solar cell due to the existence of the micro cracks.

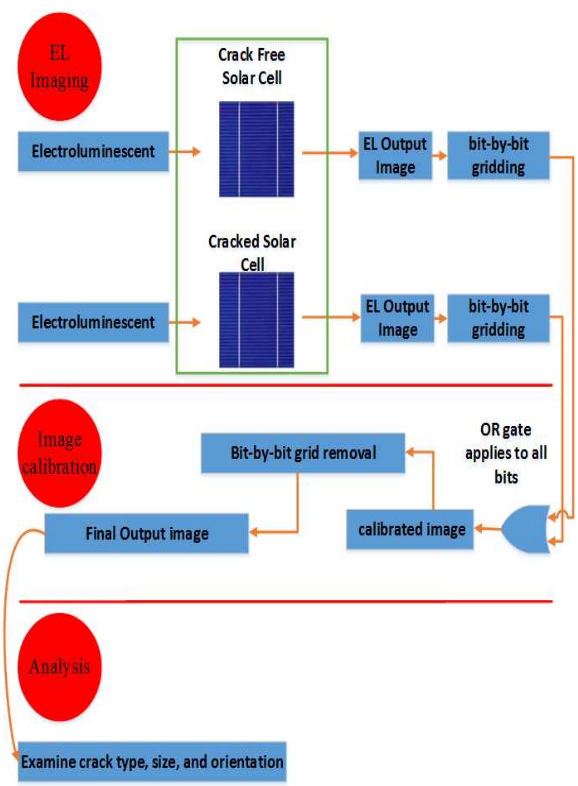


Fig. 4. Summary of the PV micro crack detection technique and its analysis procedure

IV. Evaluating the Proposed Technique on a Full Scale PV Module

In this section, the assessment of the proposed micro crack detection technique will be evaluated using a full scale image of a PV module. Fig. 5 shows an EL image of a full scale PV module, as can be noticed, multiple areas have micro cracks. The EL image does not show much information regarding the actual size and orientation of the micro cracks. Therefore, this image of the PV module will be processed into the proposed detection technique.

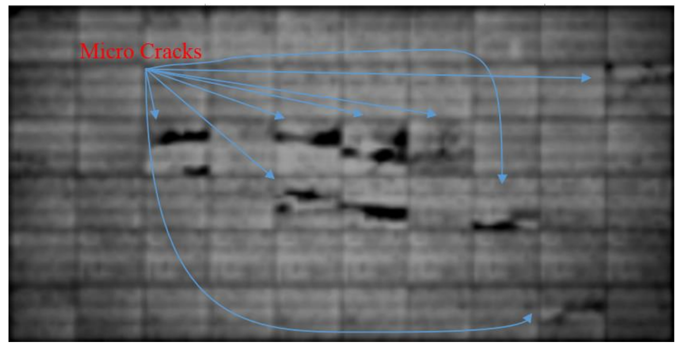
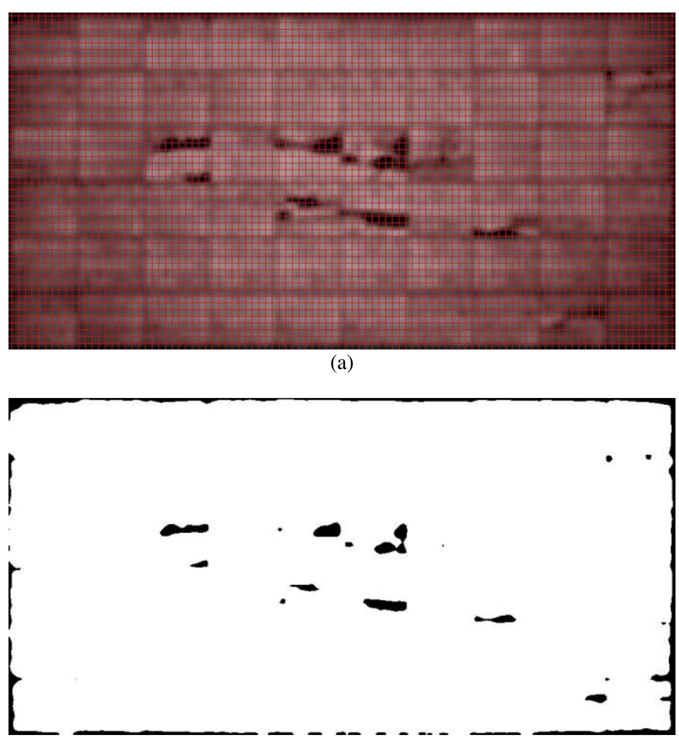


Fig. 5. EL image for a full scale PV module

Firstly, the EL image will be analysed using bit-by-bit gridding. Next, each of the bits will be processed into an OR gate with a crack free solar cell. The gridding of the EL image is shown in Fig. 6(a).

The final calibrated image of the full scale PV module is shown in Fig. 6(b), where the micro cracks location, size and orientation are clearly visible. In addition, the original image generated by the EL technique does not reflect to the actual micro cracks in the PV module, since as noted earlier, the CCD camera (specially low cost, and low resolution cameras) will add additional noise to the output EL image, therefore, the black area (corresponds to micro crack in the PV module) does not necessary corresponds to the actual crack size affecting the PV module.

In summary, the proposed technique enhanced the overall arrangement of the image, therefore, it is easier to locate the micro cracks as well as its size and orientation.



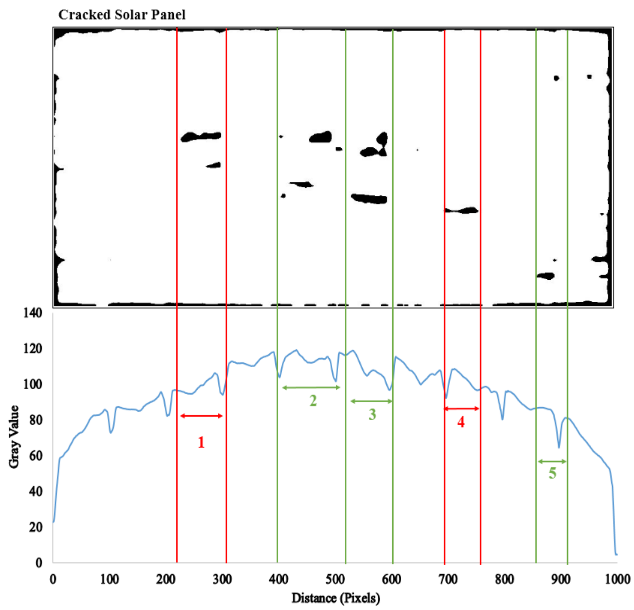
(a)

(b)

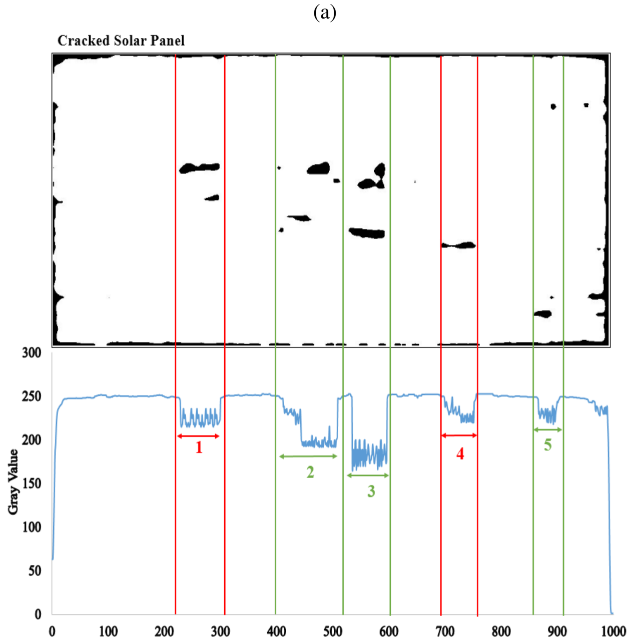
Fig. 6. (a) bit-by-bit gridding for the EL image, (b) Final output image after ORing each bit with the crack free solar cell sample

In order to better explain the output image generated by the proposed micro crack detection technique, the plot profile of the image which is well-known as the distance in pixels vs. the gray level (the level of the dark spots at each examined distance) is plotted.

Fig. 7(a) shows a mapping between the cracked PV solar module and the output plot profile of the original EL image. As can be noticed, the output gray level does not match the micro cracks, since the plot profile obtained from the original EL image does not fit with the actual variations of the cracks size, and location for the examined PV module. In addition, there is not any parameter or factor we can rely on to compare the gray level vs. the actual location of the cracks, therefore, the EL image does not give a suitable image to provide a desirable data analysis and crack detection.



(a)



(b)

Fig. 7. (a) Plot profile obtained by the original EL image, (b) Plot profile obtained by the final calibrated image after the proposed detection technique

On the other hand, the mapping between the cracked solar module with the plot profile obtained by the final calibrated image (after the proposed micro crack detection technique) is shown in Fig. 7(b). It is evident that the gray level is almost equal to 250 in crack-free/healthy areas, whereas the gray level reduces if a crack has been detected in a specific distance for the inspected PV module. This result has been attained since the final calibrated image of the micro crack shows exactly the location, size, and the orientation of the actual cracks in the PV module.

According to Fig. 7(b), five different areas contains micro cracks with different sizes are plotted and mapped accurately using the plot profile of the PV module. The gray level strongly depends on the micro crack size, location, and orientation. Area 3 had the highest loss in the gray level because the crack size at this distance is maximum among all other cracks distinguished in the PV module. The minimum gray value obtained by the plot profile presented in Fig. 7(b) are as follows: Area 1: 215; Area 2: 192; Area 3: 166; Area 4: 220; and Area 5: 218.

V. Discussion

In order to judge the appropriateness of the proposed micro crack detection technique and its output image performance. We have compared the obtained results with two other published image resolution techniques proposed in the literature.

In 2016, an interesting article done by D. Alberto et al. [17] which is one of the highly cited articles in the field of PV micro cracks detection and analysis, proposed a suitable detection method to analyse the PV micro cracks and its output power degradation on PV modules. The technique uses EL imaging to inspect micro cracks, however, authors tried to improve the detection accuracy using a thermal imaging for the cracked PV modules. Fig. 8 shows an actual image of the EL and thermal of the cracks affecting the PV module. In fact, the proposed technique lacks the following:

- The thermal image requires an additional camera which is normally high-cost (especially for a high resolution thermal camera such as FLIR). This is one of the limitations, since it requires another equipment for the detection process.
- The original EL image does not specifically presents an actual damage/micro cracks in the PV module, since as stated earlier in section III, and IV in our article, the CCD camera strongly depends on its resolution and noise filtration process.
- Last but not least, the thermal hot spots does not necessary corresponds to micro cracks, since the hot spot might be a dust [18], increase in the PV temperature [19], or snow [20].

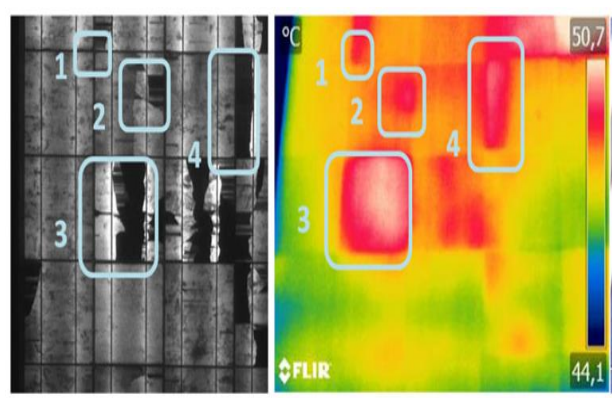


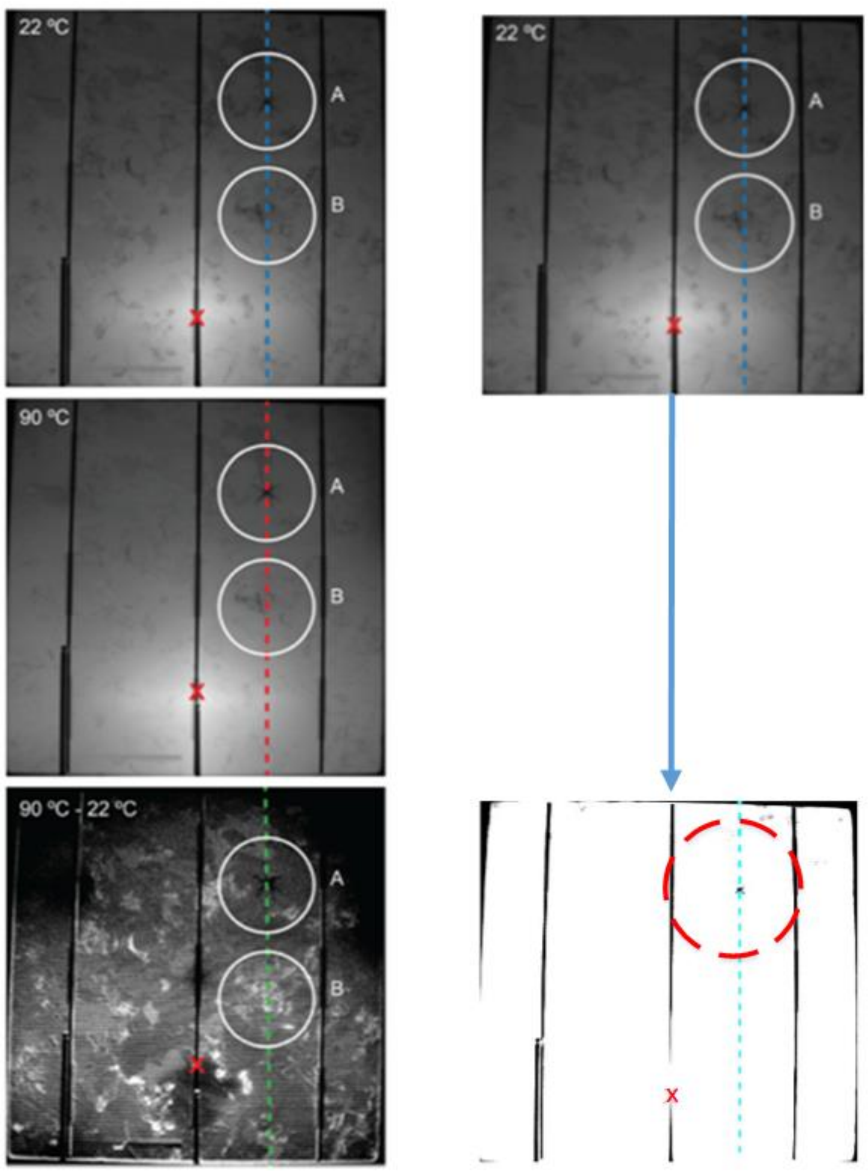
Fig. 8. Output images of the detection technique proposed by [17]

Therefore, the proposed technique in [17] does not necessary reflect to the PV micro cracks, in which we have tried to solve this problem through the proposed detection technique discussed in section III and IV, where the original EL image is captured and analysed with crack free solar cell sample, then bit-by-bit structure is obtained for both images, whereas the final stage is to process the ORing between the bits from each captured image. This technique ensures that no additional cost is required in the micro crack detection process, and it improves the output image quality, thus it is easier to identify the PV solar cells micro crack size, location and orientation.

Most recently, in 2017, M. Frazao et al. [21] proposed a consumer grade digital camera EL detection technique to inspect PV micro cracks using low cost CCD camera. The proposed technique uses a subtraction method which subtracts the EL images of the micro cracked solar cell under low and high temperature value. Fig. 9(a) demonstrates the impact of the proposed technique on the final calibrated image after subtracting the solar cell at 22 ˚C and 90 ˚C.

Circle A presents the crack in the PV solar cell, whereas circle B presents a normal cell without crack. The cracked solar cell has at 22 ˚C has been used processed using the proposed detection technique in this article, the output result is shown in Fig. 9(b). As can be noticed, the presented technique in this article does not need any further images of the solar cell, subsequently it reduces the collapse time to detect the actual crack affecting the solar cell comparing to [21] which need further image at 90 ˚C in order to get the final calibrated micro cracked solar cell image (normally needs further few minutes to do this process).

In summary, the proposed technique shows an advancement of detection for micro cracks in solar cells. The proposed technique still requires to use both healthy and the inspected solar cell image for the ORing combination. In fact, the EL image of the healthy solar cell is fairly not a drawback for the offered technique, since it can be either taken only once and reprocess the image again with any other cracked solar cell sample, or it can be taken form the manufacturer warranty datasheet, which is a common practice by PV industry nowadays to provide the hot-spot analysis as well as the EL and PL image of the solar cells.



(a) (b)

Fig. 9. (a) Output images using the detection technique proposed by [21], (b) Output images using the proposed micro crack detection technique

VI. Conclusion

In this paper, a novel detection technique based on electroluminescent imaging method is proposed to detect micro cracks affecting PV solar cells. The offered technique aims to achieve the following:

- Enhancing the EL image by using ORing method between healthy/non-cracked and cracked solar cell images.
- Improving the quality of the solar cells micro cracks thus it is easier to identify the micro cracks size, location and orientation.
- The proposed technique can be used either with distinct solar cells or large scale PV modules.
- Suggesting suitable plot profile detection method, which is well-known as the distance in pixels vs. the gray level (the level of the dark spots at each examined distance). This plot profile can be used to distinguish the cracks location and size using proper plot mechanism.

As a result, our study demonstrates that the proposed detection technique has successfully achieved the above listed targets and thus creating an up to date detection method for PV micro cracks.

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