LOW-COST ELECTROLUMINESCENCE SYSTEM FOR INFIELD PV MODULES

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ABSTRACT: As the installation of PV systems continues to decrease, the weight of the operation and maintenance in the cost structure of systems will become an ever increasing factor. The significant challenges are to maximise electrical energy production by reducing system downtime for planned and unplanned maintenance. Electroluminescence (EL) is becoming an important on-site/infield characterization technique for PV modules. However, proposed high-end EL systems may be too prohibitively expensive, eg, small systems or low-income areas. This paper demonstrates the principles a low-cost EL system for crystalline PV modules.

A consumer grade camera system (camera and lens) was modified by removal of the IR filter to allow for the band-to-band luminescent spectra to arrive at the CCD sensor. To remove background visible light, a bandpass filter tuned to approximately the luminescent spectra of silicon (1100+/-10nm) was placed before the camera lens. Open-source digital imaging processing techniques were then employed to correct geometrical image distortions and to enhance image quality.

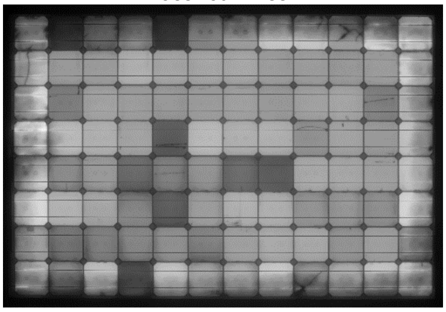
The effectiveness of the proposed system is demonstrated under three controlled conditions; indoor completely dark, indoor with controlled background lighting and, outdoor urban night-time. The system allowed for acquisition of high resolution EL images of PV modules in a matter of minutes. The quality of the images under the differing conditions are comparable. Easily visible were cracks in individual cells and also non-functioning cells of a purposefully damaged PV module.

Keywords: Silicon PV, EL, infield testing, low cost.

Indoor dark room

t = 30 s
I = 0.5A

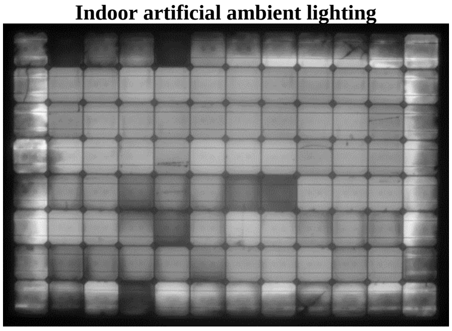
Without bandpass filter



Indoor artificial ambient lighting

t = 120 s
I = 1.5 A

With bandpass filter



Outdoor infield urban nigh-time

t = 120 s
I = 1.5 A

With bandpass filter

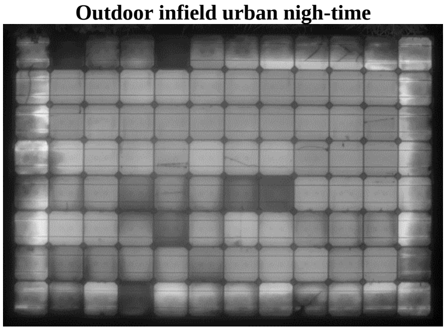


Figure shows EL images obtained under the three background lighting conditions for the same module. Images have been processed by cropping, realignment and denoising.

1. INTRODUCTION

Imaging techniques allow for short acquisition times even for large areas (up to arrays of solar modules). However, the high cost of the sensors represents the main obstacle for this approach [1], either by use of high sensitivity & low noise silicon based sensors or high cost InGaAs sensors. For infield testing of PV modules, infrared thermography and EL imaging are the most popular approaches [2, 3].

IR thermography is limited to detecting hotspots [4] at also fairly low sub megapixel resolutions. In contrast, luminescence imaging allows for the detection of including cracks, series resistance effects, bypass diode failures, light-induced degradation, potential induced degradation, and carrier induced degradation mechanisms[2].

This paper reports our new development for infield EL characterization of PV modules. In this work we achieved the following:

1) Development of EL test setup employing a modified consumer-grade digital camera coupled with a silicon band-to-band EL tuned band-pass filter;
2) Validation of the effectiveness of the proposed setup in different environments: indoor dark, indoor controlled ambient background lighting and, infield night-time measurements in an urban setting;
3) Application of simple open-source imaging processing techniques to geometrically correct and enhance images by denoising [5].

Our developed EL system is relevant when compared to other existing systems, such as the friendly daylight EL system [6], the non-stationary outdoor EL system [7], the DAYSY system [8], and the system presented by M. Frazao et al. [9]. The friendly daylight EL system [6] and the Non-stationary outdoor EL systems [7], employ costly high sensitivity industrial grade camera systems to perform outdoor daytime EL inspections. M. Frazao et al. [9] employ a consumer grade camera, however EL measurements are restricted to zero background light conditions. Our system presented here is shown to work in ambient indoor lighting conditions and also in an urban outdoor night-time environment. Table I summarizes and compares the referenced systems with the one presented introduced here.

Table 1: Comparison between other existing and our EL system.

System[reference]	A friendly daylight EL system[6]	Non-stationary outdoor EL system [7]	DAYSY system[8]	System A[9]	Our system
Medium	Outdoor-Sun	Outdoor -Sun	Outdoor -Sun	Dark	Outdoor - Night
Camera type	Cost-effective InGaAs CCD-320x256 pixels	InGaAs CCD-320x256 pixels	-InGaAs CCD*-320x256 pixels	a consumer digital camera CCD-3000x2000 pixels	a consumer digital camera CCD-3000x2000 pixels
Imaging	EL & PL	EL	EL & PL	EL	EL
Exposition Time	Less than 20 s.	1 ms - 20 ms	60 s- 120 s	6 min	30 s -120 s
Filter	Appropriate filter setup	-	digital filtering techniques	NO	Hardware band pass filter

*Information not available, but is inferred by the general characteristics presented by the manufacturer of the DaySy system.

The remainder of this paper is organized as follows: Section 2 introduces the proposed EL test setup and methodology. Section 3 discusses the result, and conclusion are presented in Section 4.

2. METHODOLOGY

2.1 The proposed electroluminescence setup

Figure 1 shows the experimental setup. The PV modules are connected to a DC power supply by using standard solar cabling and connectors. The digital camera used was a modified Nikon D40 whereby the internal IR filter was removed. A bandpass filter (Melles Griot 03 F11 024, 1100 nm +/- 5 nm) was mounted in front of the lens to remove background light. Automatic image acquisition was operated via a PC with propriety camera software. This limited automatic acquisition times to 30 s. For longer acquisition times, the camera shutter had to be depressed manually operating the via the bulb mode.

Figure 1: The proposed Electroluminescence setup, the setup consists of the (1) power supply, (2) PV module, (3) band-pass filter, (4) digital camera,(3x AF-S DX Zoom-NIKKOR 18-55mm f/3.5-5.6G ED II lens) (5) USB cable (5), and (6) PC.

The EL imaging is undertaken in three conditions: 1) a dark room; 2) a room with normal working indoor lighting conditions and; 3) outdoors under urban night conditions.

Figure 2 is a schematic representation of the intersection of the EL, camera sensitivity and, bandpass spectra. Although the Si CCD sensor is not particularly senstive where Si EL is strongest, if background stray light can be removed, then it is simply a question of

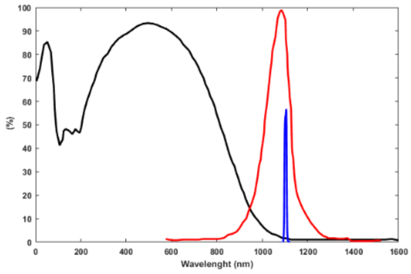


Figure 2: The typical relative emission spectrum of Si, Si-CCD quantum efficiency, and bandpass filter transmission spectrum [1].

extending acquisition times to obtain usable images. The bandpass filter employed has a peak transmissivity of ca 50%, and a fairly narrow bandwith (ca +/- 5 nm FWHM), and as such will also block a significat fraction of the EL emission.

2.2 The EL image processing algorithm

Upon acquisition of the EL images, the following digital processing steps was undertaken:

Step 1 geometric correction: Perspective Correction algorithm which introduced described by Bedrich [5] was applied to correct the position and rotation of the image. This algorithm includes two stages, image grid generation and image cell rectification.

Step 2 denoising: A non-local means denoising algorithm [10] was used to remove the noise of the image. The main concept of this algorithm is to replace the intensity of a target pixel with a weighted average of the neighbouring pixels.

Figure 3 illustrates the implementation of the imaging processing steps on a EL image of a PV module.

Infield EL image **Step 1: Image after geometrical correction** **Step 2: Image after denoising**

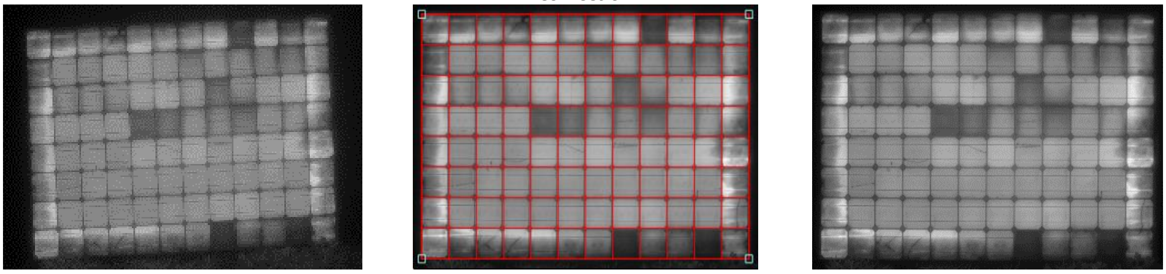


Figure 3: Example of implementing of the EL image processing algorithm

3. RESULTS and DISCUSSION

Shown in figure 4 are EL images (as taken and then digitally processed) of a PV module taken under different background lighting conditions. The images are angled so as to demonstrate the capabilities of the geometric correction of the image processing algorithms employed.

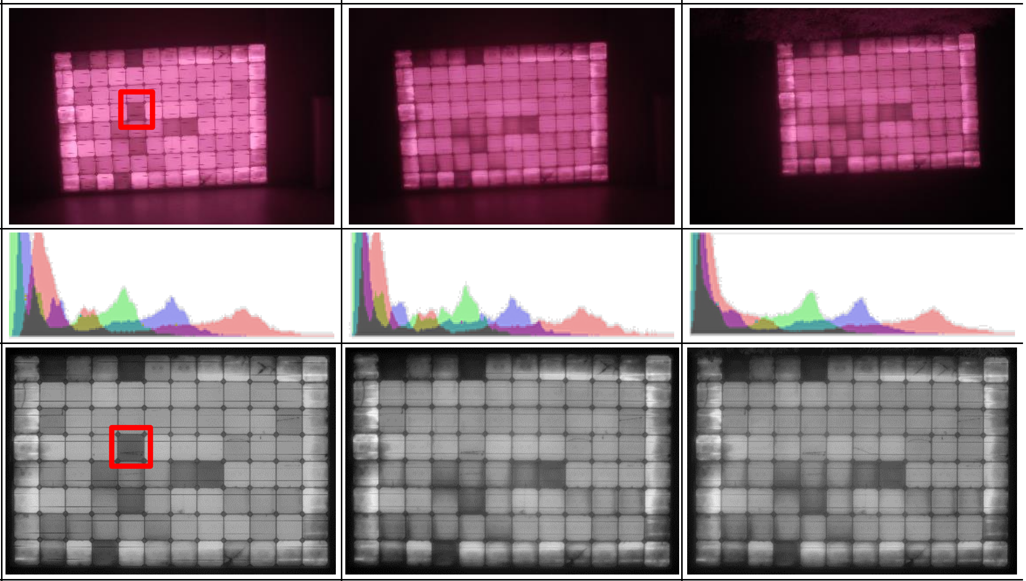
Although the IR filter is removed from the camera, individual red, blue and green (RGB) pixels still have broadband colour selective filters. In essence the green and blue pixels have a significantly lower signal than that of the red pixels. However, because the blue filter is more transparent to the IR than the green filter, the blue signal is stronger and, as such, when viewed along with the strong red signal, the apparent colour is purple.

Bias of the PV module and image acquisition time was adjusted so as to maximise the dynamic range of the images (without saturating the image). Images taken with the bandpass filter to remove the background visible light required a higher forward biasing of the PV module and hence higher currents (0.5 A vs 1.5 A) and, also required longer acquisitions times (30 s vs 120 s). This is evident from the histograms presented, where a large pixel intensity count occurs at ca 80% of the maximum pixel intensity. It is important to note that the background ambient illumination conditions were such that the images would quickly saturate without the use of the IR bandpass filter.

The images here presented with the bandpass filter are slightly blurred. This is due to the mechanical shake suffered by the camera during the long expositions (>30 s) where manual depressing of the shutter button was required.

Overall the images obtained are similar irrespective of the conditions. However, highlighted is a cell which appears darker in the dark room EL image when compared with the other two conditions which employed a band-pass filter and hence required higher current densities.

The automatically digitally processed images are also shown in Figure 4 and demonstrate that the algorithm is successful at correcting the image geometry and enhancing the image so as to allow for more facile defect identification on the module.



	Dark room Without bandpass filter	Room with ambient light With bandpass filter	Infield night-time With bandpass filter
Exposure time	**30 s**	**120 s**	**120 s**
Bias current	**0.5 A**	**1.5 A**	**1.5 A**
Aperture	**f/4**	**f/4**	**f/4**
ISO	**200**	**200**	**200**

Figure 4: EL images before and after digital processing for a PV module under different background lighting conditions. The red square box highlights a dark cell in the darkroom EL image, which is not dark under the other two lighting conditions.

4. CONCLUSIONS

The acquisition of high quality infield night time EL images has been shown to be possible with recourse to a lightly modified consumer grade Si CCD camera coupled with a standard bandpass filter along with the enhancement of image quality using open-source image processing algorithms. The images are shown to be of similar quality to those obtained in controlled absolute dark conditions. This paves the way to the development of low-cost EL imaging systems that maybe of vital importance for the widespread implementation of reliable functioning of PV systems for, eg, rural electrification in low income areas.

ACKNOWLEDGEMENTS

Mr. M. Abdullah Eissa acknowledges the student bursary provided by the Erasmus + Medsol student and staff training program.

Prof. K. Lobato, Dr. J. Silva and Prof. J. M. Serra aknowledge the Portuguese Science & Technology Foundation (FCT) for funding through the R&D strategic project funding project UID/GEO/50019/2013.

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Motivation

PV manufacture costs have decreased significantly.

Operation and Maintenance (O&M) of PV systems is becoming evermore a relevant cost factor.

PV system downtime, for scheduled and unscheduled maintenance, has to be minimized.

Electroluminescence (EL) is powerful lab scale characterization technique.

EL is also evermore important for infield characterization of PV modules and systems.

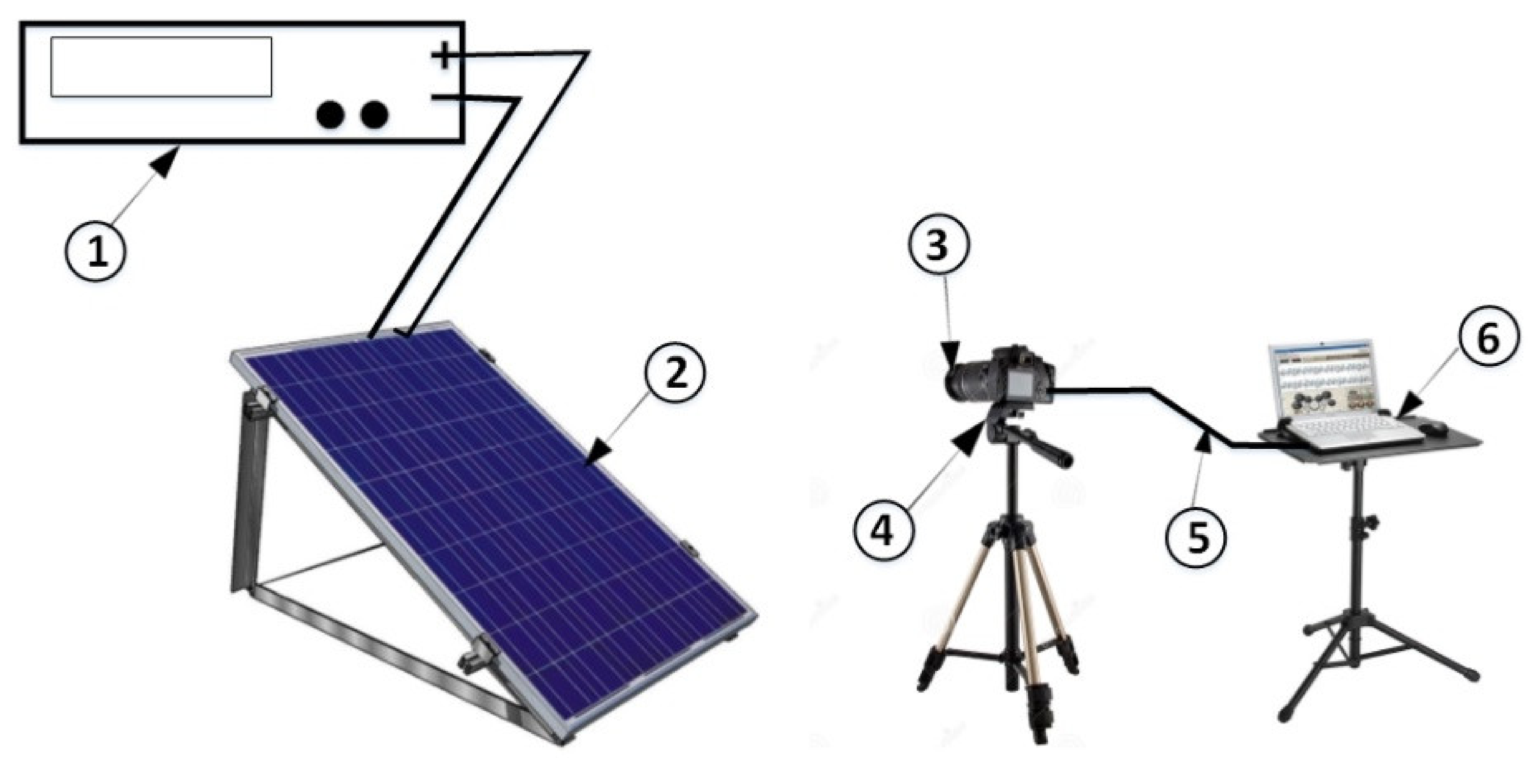
However, current EL systems are still **prohibitively costly for small systems or low-income areas**.

Objectives

Develop a low-cost imaging system that can perform EL imaging of PV modules in infield conditions.

Experimental Setup

1. DC power source
2. PV module, multicrystalline Si
3. Bandpass filter (1100nm +/- 10nm FWH)
4. Consumer grade CCD DSLR camera
5. & 6. PC control of camera



Methods

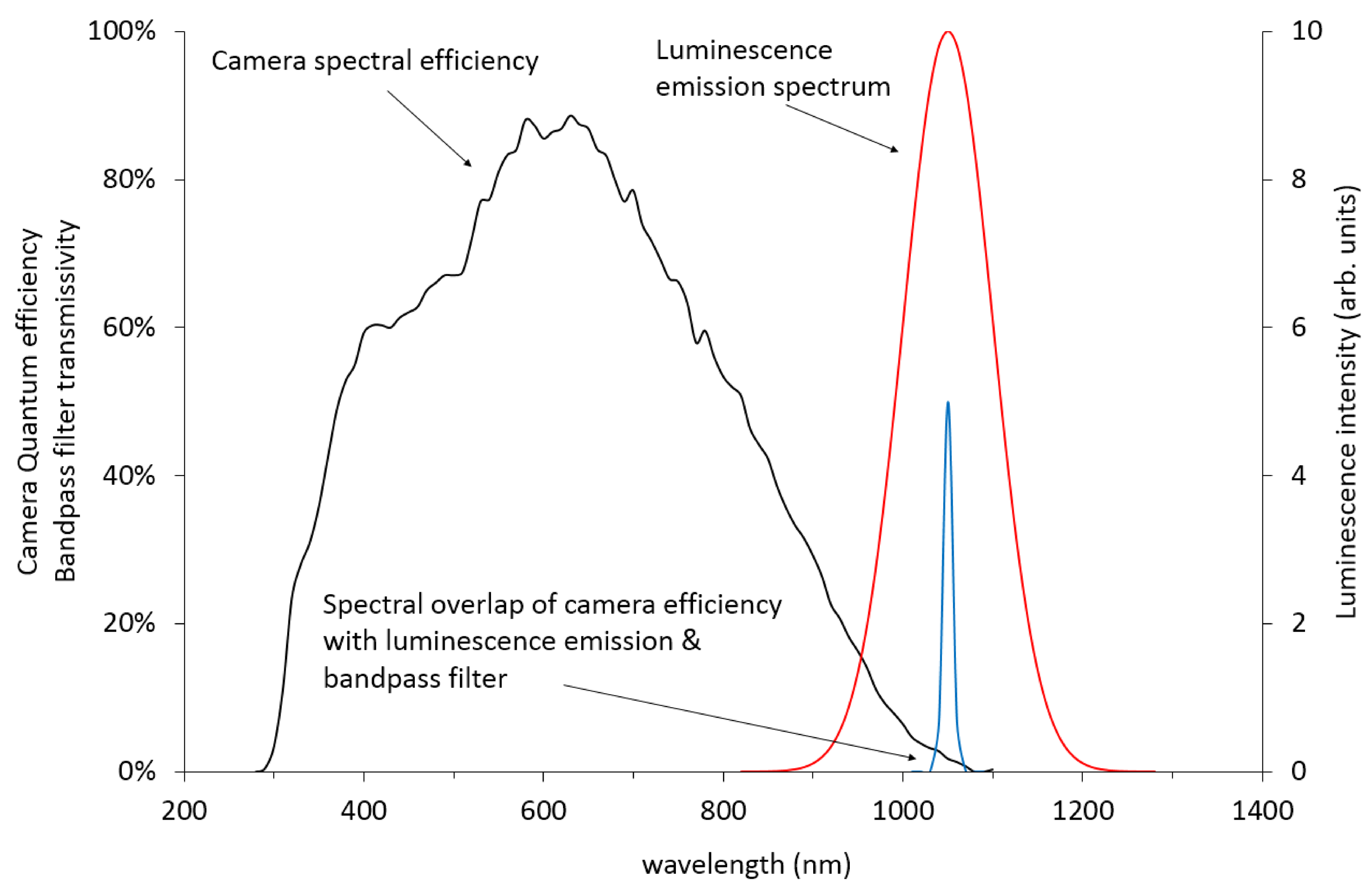
PV module was connected to a DC power source under a forward bias voltage close to the module's open circuit voltage.

Image acquisition was undertaken in the following conditions:

- indoors with and without optical band-pass filter to understand the camera sensitivity and parameters and for differing applied voltage biases;
- outdoors at night with and without optical band-pass filter.

Use of open-source software for image processing, namely orientation correction and denoising.

The band-pass filter is highly transparent in 1100 +/- 5 nm band thus filtering background visible light from the camera whilst still permitting the detection of luminescence.



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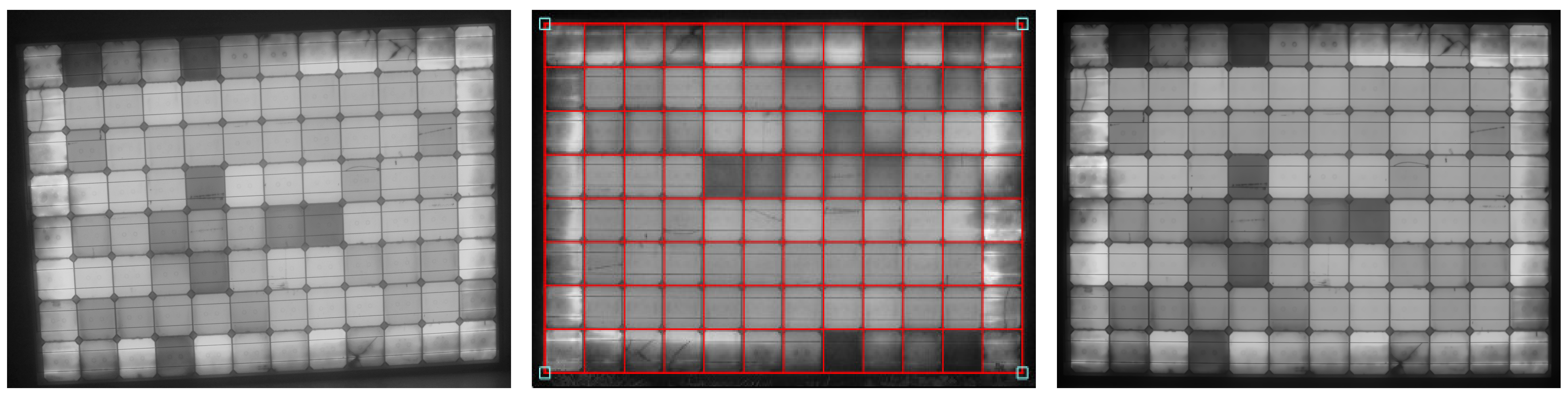
Results

Image processing

Images below show the result of a two step image enhancement processing:

Step 1 geometric correction: Perspective Correction algorithm was applied to correct the position and rotation of the image. This algorithm includes two stages, image grid generation and image cell rectification.

Step 2 denoising: A non-local means denoising algorithm was used to remove the noise of the image. The main concept of this algorithm is to replace the intensity of a target pixel with a weighted average of the neighbouring pixels.



Original image **Step 1** **Step 2**

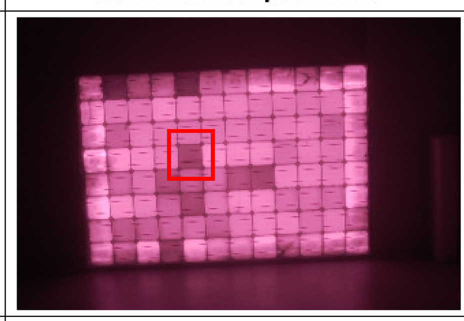
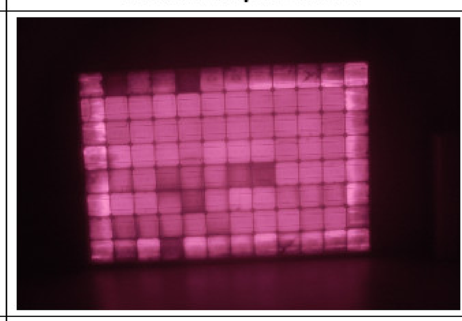
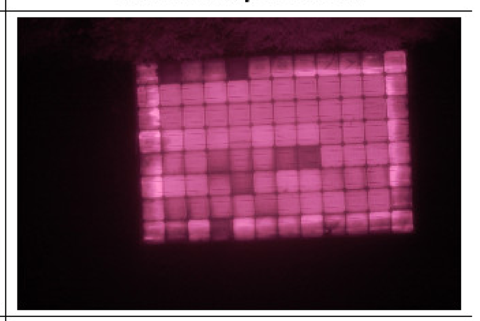
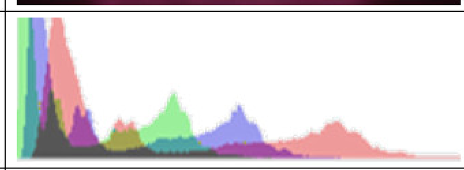
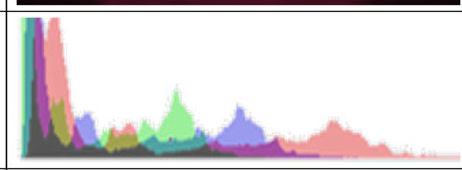
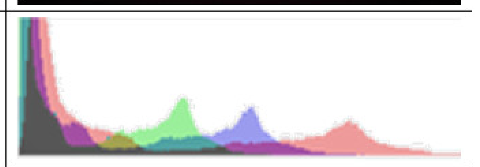
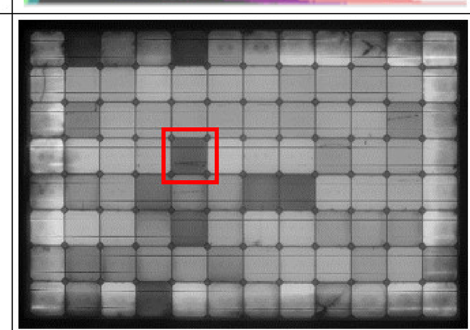
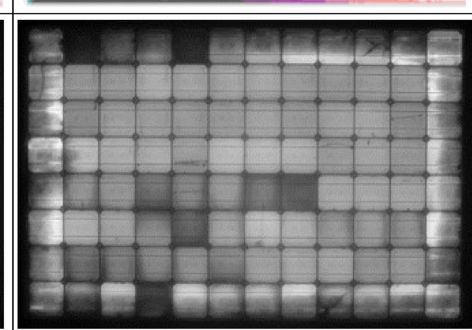
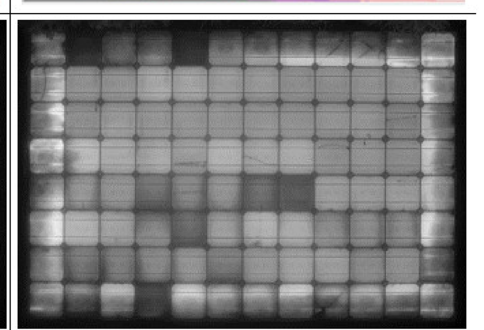
Indoor versus outdoor image acquisition and processing

Image acquisition when using the bandpass filter requires

- Longer acquisition
- Greater forward bias voltage so as to have a higher current and hence higher luminescence intensity

No discernable quality difference between images acquired under ideal indoor conditions and those acquired in outdoor real-world conditions.

The red square box highlights a dark cell in the darkroom EL image, which is not dark under the other two lighting conditions. This a result of a higher applied bias for the former.

	Dark room Without bandpass filter	Room with ambient light With bandpass filter	Infield night-time With bandpass filter
Original Image			
RGB histogram			
Processed image			
Exposure time	30 s	120 s	120 s
Bias current	0.5 A	1.5 A	1.5 A
Aperture	f/4	f/4	f/4
ISO	200	200	200

Conclusions

A cost-effective system is here demonstrated and shown to work effectively for:

- Indoors (completely dark conditions);
- Indoors with standard indoor lighting;
- Outdoors under standard street light conditions.

The quality of the images under the differing conditions are comparable.
Easily visible were cracks in individual cells and also non-functioning cells of a purposefully damaged PV module.

Acquisition times of under a minute are feasible for small PV systems that are composed of only a handful of modules.

Paves the way for the widespread implementation of EL luminescence imaging of PV systems.

Outlook

System to be tested on real PV module system installed eg rooftop or in a field. Can images of sufficient quality be captured for a complete set of modules in one go?

Use of bipolar imaging techniques to remove excess background visible and IR light so as to permit image acquisition under more demanding nighttime conditions or possibly under daylight conditions.

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ABSTRACT: As the installation of PV systems continues to decrease, the weight of the operation and maintenance in the cost structure of systems will become an ever increasing factor. The significant challenges are to maximise electrical energy production by reducing system downtime for planned and unplanned maintenance. Electroluminescence (EL) is becoming an important on-site/infield characterization technique for PV modules. However, proposed high-end EL systems may be too prohibitively expensive, eg, for small systems or low-income areas. This paper demonstrates the principles a low-cost EL system for crystalline PV modules. A consumer grade camera system (camera and lens) was modified by removal of the IR filter to allow for the band-to-band luminescent spectra to arrive at the CCD sensor. To remove background visible light, a bandpass filter tuned to approximately the luminescent spectra of silicon (1100+/-10nm) was placed before the camera lens. Open-source digital imaging processing techniques were then employed to correct geometrical image distortions and to enhance image quality. The effectiveness of the proposed system is demonstrated under three controlled conditions; indoor completely dark, indoor with controlled background lighting and, outdoor urban night-time. The system allowed for acquisition of high resolution EL images of PV modules in a matter of minutes. The quality of the images under the differing conditions are comparable. Easily visible were cracks in individual cells and also non-functioning cells of a purposefully damaged PV module.
Keywords: Silicon PV, EL, infield testing, low cost.

1 INTRODUCATION

Imaging techniques allow for short acquisition times even for large areas (up to arrays of solar modules). However, the high cost of the sensors represents the main obstacle for this approach [1], either by use of high sensitivity & low noise silicon based sensors or high cost InGaAs sensors. For infield testing of PV modules, infrared thermography and EL imaging are the most popular approaches [2, 3].

IR thermography is limited to detecting hotspots [4] at also fairly low sub-megapixel resolutions. In contrast, luminescence imaging allows for the detection of cracks, series resistance effects, bypass diode failures, light-induced degradation, potential induced degradation, and carrier induced degradation mechanisms [2].

This paper reports our new development for infield EL characterization of PV modules. In this work we achieved the following:

1) 1) Development of EL test setup employing a modified consumer-grade digital camera coupled with bandpass filter to remove background stray light;
2) 2) Validation of the effectiveness of the proposed setup in different environments: indoor dark, indoor controlled ambient background lighting and, infield night-time measurements in an urban setting;
3) 3) Application of simple open-source imaging processing techniques to geometrically correct and enhance images by denoising [5].

Our developed EL system is relevant when compared to other existing systems, such as the friendly daylight EL system [6], the non-stationary outdoor EL system [7], the DAYSY system [8], and the system presented by M. Frazao et al. [9]. Table 1 summarizes and compares the referenced systems with the one presented introduced here. The friendly daylight EL system [6] and the Non-stationary outdoor EL systems [7], employ costly high sensitivity industrial grade camera systems to perform outdoor daytime EL inspections. M. Frazao et al. [9] employ a consumer grade camera, however EL measurements are restricted to zero background light conditions. Our system presented here is shown to work in ambient indoor lighting conditions and also in an urban outdoor night-time environment.

The remainder of this paper is organized as follows: Section 2 introduces the proposed EL test setup and methodology, section 3 discusses the result, and conclusion are presented in Section 4.

2 METHODOLOGY

2.1 The proposed electroluminescence setup

Figure 1 shows the experimental setup. The PV modules are connected to a DC power supply by using standard solar cabling and connectors. The digital camera used was a modified Nikon D40 whereby the internal IR filter was removed. A bandpass filter (Melles Griot 03 F11 024, 1100 nm +/- 5 nm) was mounted in front of the lens to remove background ambient light. Automatic image acquisition was operated via a PC with propriety camera software. This limited automatic acquisition times to 30 s. For longer acquisition times, the camera shutter had to be depressed manually operating the via the bulb mode. The EL imaging is undertaken in three conditions: 1) a dark room; 2) a room with normal working indoor lighting conditions and; 3) outdoors under urban night conditions.

Figure 2 is a representation of the intersection of the EL, camera sensitivity and, bandpass spectra. The represented camera spectrum is that of a scientific grade camera. Data is confidential and as such camera model cannot be divulged. To this date, it has not been possible to obtain quantum efficiency data of the consumer grade camera used in here. Although the Si CCD sensor is not particularly sensitive where Si EL is strongest, if background stray light can be removed, then it is simply a

Table 1: Comparison between other existing and our EL system

System[ref.]	A friendly daylight EL system[6]	Non-stationary outdoor EL system [7]	DAYSY system[8]	System A[9]	Our system
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Imaging	EL & PL	EL	EL & PL	EL	EL
Exposition time	Less than 20 s.	1 ms - 20 ms	60 s- 120 s	6 min	30 s -120 s
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Figure 1: The proposed Electroluminescence setup, the setup consists of the (1) power supply, (2) PV module, (3) bandpass filter, (4) digital camera, (Nikon D40 with a 18-55mm f/3.5-5.6G ED II lens) (5) USB cable (5), and (6) PC.

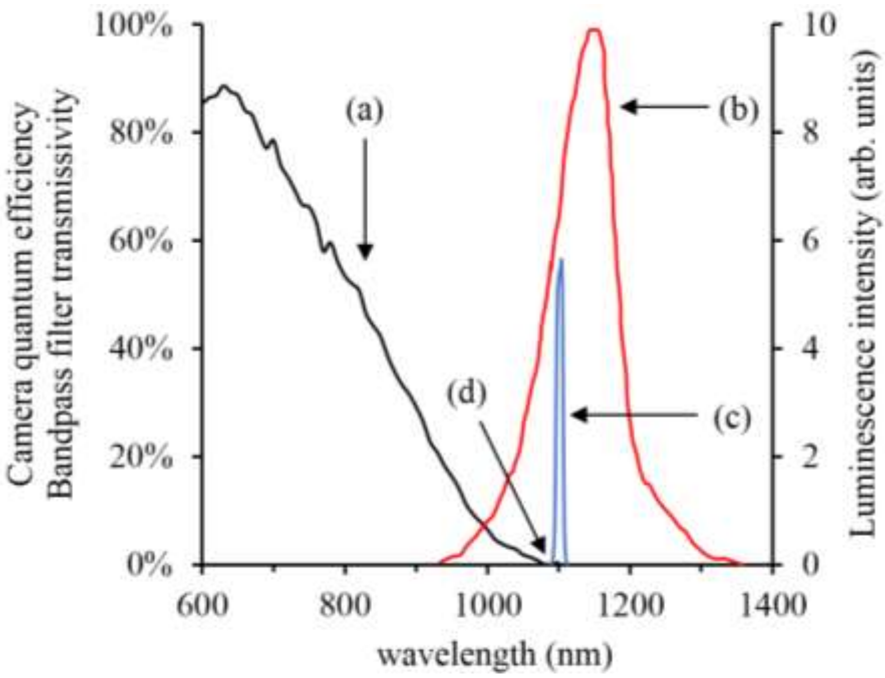

Figure 2: (a) Spectral quantum efficiency of a scientific grade silicon CCD camera. (b) Example of typical luminescence spectrum of a silicon solar cell [1]. (c) Transmission spectrum of the 1100 nm bandpass filter, Melles Griot 03-F11-024. (d) Spectral overlap of camera quantum efficiency, expected luminescence and bandpass filter.

question of extending acquisition times to obtain usable images. The bandpass filter employed has a peak transmissivity of ca. 50%, and a fairly narrow bandwidth (ca +/- 5 nm FWHM), and as such will also block a significant fraction of the EL emission. Tests were undertaken with a 1050 nm bandpass filter with the expectation that in this spectral region the image acquisition would be enhanced. However, the opposite was observed, indicating that at this wavelength the spectral intensity of the tested modules is significantly lower than expected from the example spectrum shown.

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2.2 The EL image processing algorithm

Upon acquisition of the EL images, a two-step algorithm was employed for image geometric correction and image quality enhancement.

Step 1 geometric correction: Perspective Correction algorithm which introduced described by Bedrich [5] was applied to correct the position and rotation of the image. This algorithm includes two stages, image grid generation and image cell rectification.

Step 2 denoising: A non-local means denoising algorithm [10] was used to remove the noise of the image. The main concept of this algorithm is to replace the intensity of a target pixel with a weighted average of the neighbouring pixels.

Error! Reference source not found. illustrates the implementation of the imaging processing steps on an EL image of a PV module.

3 RESULTS AND DISCUSSION

Shown in table 2 are EL images (as taken and then digitally processed) of a PV module taken under different background lighting conditions. The images are angled so as to demonstrate the capabilities of the geometric correction of the image processing algorithms employed.

Although the IR filter is removed from the camera, individual red, blue and green (RGB) pixels still have broadband colour selective filters. In essence the green and blue pixels have a significantly lower signal than that of the red pixels. However, because the blue filter is more transparent to the IR than the green filter, the blue signal is stronger and, as such, when viewed along with the strong red signal, the apparent colour is purple.

Bias of the PV module and image acquisition time was adjusted so as to maximise the dynamic range of the images (without saturating the image). Images taken with the bandpass filter to remove the background visible light required a higher forward biasing of the PV module and hence higher currents (0.5 A vs 1.5 A) and, also required longer acquisitions times (30 s vs 120 s). This is evident from the histograms presented, where a large pixel intensity count occurs at ca 80% of the maximum pixel intensity. It is important to note that the background ambient illumination conditions were such that the images would quickly saturate without the use of the IR bandpass filter.

The images here presented with the bandpass filter are slightly blurred. This is due to the mechanical shaking suffered by the camera during the long expositions (>30 s) where manual depressing of the shutter button was required.

Overall the images obtained are similar irrespective of the conditions. However, highlighted is a cell which appears darker in the dark room EL image when compared with the other two conditions which employed a bandpass filter and hence required higher current densities.

The automatically digitally processed images are also shown in table 2 and demonstrate that the algorithm is successful at correcting the image geometry and enhancing the image so as to allow for more facile defect identification on the module.

4 CONCLUSION

The acquisition of high quality infield night time EL images has been shown to be possible with recourse to a lightly modified consumer grade Si CCD camera coupled with a standard bandpass filter along with the enhancement of image quality using open-source image processing algorithms. The images are shown to be of similar quality to those obtained in controlled absolute dark conditions. This paves the way to the development of low-cost EL imaging systems that maybe of vital importance for the widespread implementation of reliable functioning of PV systems for, eg, rural electrification in low income areas.

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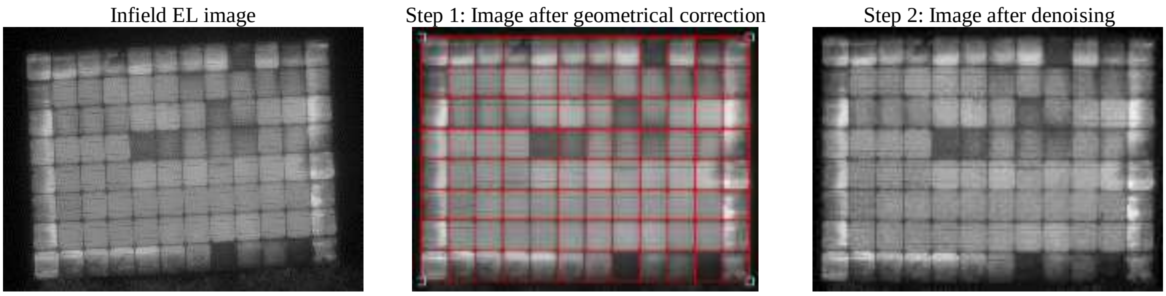
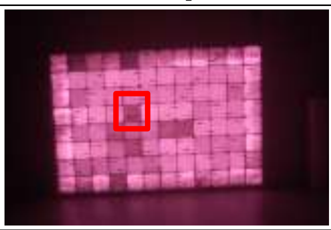
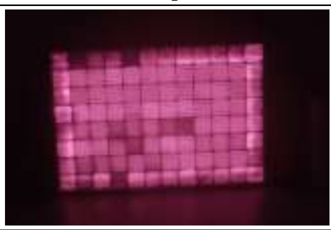
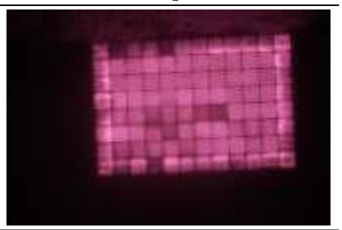
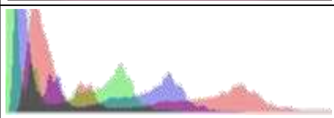
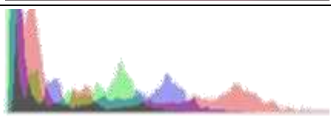
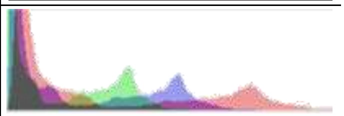
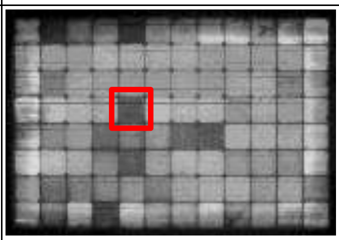
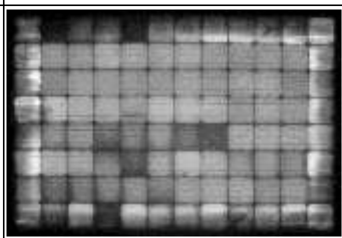
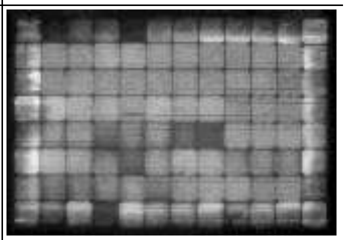


Figure 3: Example of the EL image processing algorithm.

Table 2: EL images before and after digital processing for a PV module under different background lighting conditions. The red square box highlights a dark cell in the darkroom EL image, which is not dark under the other two lighting conditions. The forward bias

	Dark room Without bandpass filter	**Room with ambient light With bandpass filter**	**Infield night-time With bandpass filter**
Original Image			
RGB histogram			
Processed image			
Bias current	0.5 A	1.5 A	1.5 A
Exposure time	30 s	120 s	120 s
Aperture	f/4	f/4	f/4
ISO	200	200	200