Luminescence imaging of solar modules in full sunlight using ultranarrow bandpass filters

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Abstract
Photovoltaic (PV) electricity generation is the fastest growing energy source globally and also humanity’s best opportunity to achieve the urgently required deep decarbonisation of the energy sector. As PV enters the terawatt scale, with millions of modules in a single PV power plant, quality testing of installed PV modules becomes indispensable to guarantee PV as a reliable long-term source of electricity. We present a method that extends the use of photoluminescence (PL) imaging to field-deployed solar modules in full sunlight. The method takes advantage of sunlight absorption in the Earth’s atmosphere in a narrow spectral range around 1,135-nm wavelength and recent developments in ulranarrow bandpass optical filter technology. The technical principles and experimental data are provided. This method lays the foundations for PL imaging, a powerful inspection method for the PV industry and research, to be applied to routine high-volume inspection of fielded PV modules on large-scale solar power plants.

KEYWORDS
metrology, photoluminescence, photoluminescence imaging, photovoltaic inspection, ultranarrow bandpass filter, quality control

1 | INTRODUCTION

Solar photovoltaics (PVs), the direct generation of electricity from sunlight, now provides the cheapest source of electricity in large parts of the world, often undercutting even the incremental costs of existing fossil fuel-based power stations. Record low bids for electricity supply of just US$10.4/MWh (equivalent to just over 1 c/kWh) from a 600-MW PV power plant were recently reported. As such, solar PV—and in particular silicon-based PVs—is poised as the prime technology for the urgently required rapid and deep decarbonisation of the global economy. Both the PV technology and PV industry are ready to deliver the needed clean energy systems, with the largest utility-scale power plants already reaching gigawatt scale containing several million modules per PV power plant. Quality testing of all or at least a statistically relevant fraction of installed modules is critical to mitigate financial risk, to ensure long-term stability, to assess damage after extreme weather events and to guarantee reliable system power output. With high measurement throughput, drone-based infrared thermography is currently used most commonly for large-scale module inspection by detecting infrared heat emission. Electro luminescence (EL) and photoluminescence (PL) imaging techniques enable much more detailed and accurate fault analysis, defect detection and defect classification. Not surprisingly, those techniques are now almost universally used in PV research and manufacturing. Especially, PL imaging, owing to its contactless nature, can be applied to ingots, wafers, cells and modules with high throughput and has been a core enabling technology behind the breathtaking PV technology developments over the last 1.5 decades. However, higher complexity and specific practical limitations have so far limited the adoption of these techniques for routine solar...
power plant inspection. For instance, modification to the electrical wiring of operating PV systems, required to achieve current injection for EL imaging, is problematic in relation to safety concerns and comes with limited measurement throughput and increased cost. These constraints can be avoided in PL imaging; however, uniform full area illumination of industrial-sized modules (area up to >3 m²) using lasers or light emitting diodes commonly used as excitation sources in laboratory and commercial PL imaging systems is, in principle, possible but impractical for high-volume inspection on operating solar power plants. For daylight inspection, the sun itself would be an ideal excitation source but would require separation of the very weak luminescence signal from orders of magnitude more intense reflected and scattered sunlight. In laboratory PL imaging systems, the excitation light is passed through customised dielectric filter stacks (clean up filters) that block any spectral components within the spectral sensitivity range of the camera. Using that same approach for field inspection under sunlight excitation would require impractically large and expensive filters. Lock-in imaging approaches requiring electrical or optical toggling of the luminescence emission by periodic switching of the module's electrical operating point are associated with various undesirable and time-consuming complications, and hence severely limit the adoption of PL inspection in PV power plants. Here, we present a radically different approach, referred to below as direct PL imaging that enables luminescence image acquisition with a single camera shot, with no need for complications such as modulating the operating point of individual modules.

As recently as 2001, it was thought that silicon's indirect bandgap prevented it from emitting measurable light efficiently without enhancement, such as by carrier confinement. Subsequent work showed that features incorporated into silicon solar cells to boost performance simultaneously increased light emission—a generalisation of Kirchhoff's law linking absorption and emission—with 1% 'wall-plug' efficiency demonstrated. This soon led to the use of charge-coupled devices in full sunlight. In laboratory PL imaging systems, the wide atmospheric absorption band from 1,110 to 1,165 nm, formed by thousands of individual water vapour absorption lines. Our work is based on the realisation that a particularly high density of strong absorption lines leads to almost complete blocking of sunlight reaching the Earth's surface over an ultranarrow spectral band near 1,135 nm (Figure 1A, inset). In direct PL imaging, we use the atmospheric absorption within this narrow spectral band as a natural notch clean-up filter for the excitation light source (the sun). Restricting the camera sensitivity to that spectral band, using a customised UNBPF and camera lens, as described below, enables direct PL imaging with a single camera acquisition.

The spectral transmission specifications required for the UNBPF depend on the AM crossed by sunlight before it strikes the Earth's surface and the water vapour concentration, the latter expressed in its equivalent of liquid water height (water vapour column or WVC). The expected WVC varies significantly across the globe and seasonally. As a general trend, WVC increases with latitude from the poles towards the equator and is generally higher at lower elevations and during the summer period. In the calculations of the atmosphere's transmission, we assumed an effective WVC (AM × WVC) of 3 cm, which describes summer conditions in a wide range of climates but excludes polar regions and high-altitude areas. For the assumed conditions, the atmospheric blocking band spans the spectral range from 1,134.5 to 1,135.3 nm (Figure 1C). A UNBPF was designed to match this specific atmospheric absorption band. A typical feature of interferometric filters is a spectral blue shift of the passband with increased angle of incidence (AOI). The transmittance band of the UNBPF blue shifts by 0.18 nm from 0° to 2° AOI (solid and dashed red lines, respectively in Figure 1C). This shift of the passband is small in absolute terms, but large relative to the narrow atmospheric absorption band, representing a significant technical challenge for direct PL imaging. Therefore, the optimised UNBPF has a spectral bandwidth of only 0.34 nm and a centre wavelength of 1,134.98 ± 0.03 nm for normal incidence, slightly red shifted compared with the centre of the atmospheric absorption band, allowing optimal filter performance for AOI up to 2° (Figure 1C and Figure S1c,d). A customised lens arrangement, containing the UNBPF in its telecentric space, allows imaging objects with a much wider viewing angle, while maintaining the AOI on the UNBPF inside the telecentric lens below 2°, enabling direct PL imaging of PV modules up to 2 m in size with a camera working distance of about 8.3 m.

Direct PL imaging was applied to two modern, full size industrial monocrystalline silicon half-cell PV modules, a first module manufactured using so-called passivated emitter and rear contact solar cells (PERCs) currently dominating PV manufacturing with...
>90% market share, and a second module using heterojunction (HJT) solar cells. While not yet widely adopted in the market, HJT technology is seen as one of several contenders for the next generation of mass produced high-efficiency industrial PV devices. 

PL images of HJT modules exhibit a higher signal to noise ratio compared with images of PERC modules, when measured under identical conditions, consistent with significantly higher open-circuit (OC) voltage per cell (735 mV/cell for HJT, compared with 686 mV/cell for PERC). PL images were acquired on the two test modules under OC conditions on the UNSW campus in Sydney, Australia on a sunny day in March around mid-day. Mechanical stresses were intentionally applied to both modules prior to the experiments, to induce microcracks: mechanical defects known to create distinct PL features, but invisible to the eye and typically created during rough transportation or installation, or extreme weather events.

A full area PL image of the HJT module (Figure 2A) and a close-up of particular cells within the same module (Figure 2B), both measured with 20-s acquisition time, show microcracks as very pronounced defects. The PL image of the HJT module also shows variations in the PL intensity, indicative of quality variations between cells within the module. Microcracks can also clearly be identified in the PL images on the PERC module, measured with acquisition times of 50 (Figure 2C) and 1 s (Figure 2D), respectively. Importantly, none of these defects are visible with the naked eye or with conventional optical inspection systems. The raw camera signal in these experiments contained >98% PL signal for the HJT module and >92% of PL signal for the PERC module, confirming the very effective blocking of sunlight by the atmospheric water vapour and UNBPF combination. Excellent agreement was observed with EL and PL images measured on the same modules, but under controlled laboratory conditions and using commercial luminescence imaging equipment (Figure S2f), providing further evidence for the viability of direct PL imaging.

Interestingly, the PL signal in direct PL imaging data was found to increase with shorter camera working distance (Figure S2e), which is
attributed to partial absorption of the PL signal by water vapour on its path from the module to the camera, consistent with an optical absorption length of 12 m in that spectral range.

The acquisition times used for direct PL imaging were chosen to maximise the image quality. The direct PL image of the PERC module that was measured with a short exposure time of only 1 s (Figure 2D) demonstrates that reliable defect detection from direct PL imaging on industrial modules can be achieved with rather short measurement time per module. Substantial reductions of the acquisition time are expected by further improvements in the imaging setup, including use of an optimised telecentric lens with higher optical throughput and a lower noise camera. A reduction of the acquisition time for full area PERC modules to 0.1 s appears feasible. Such short acquisition times enable a throughput of up to 1.5 MW/h, for example when used in conjunction with unmanned aerial vehicles.
PL images on solar cells and modules measured under illumination and with simultaneous current extraction exhibit an inverted luminescence contrast compared with EL images around areas of increased effective series resistance, which allows unambiguous defect classification. Series resistance defects are commonly observed in PV modules and can be the source of hot spots and increased degradation. Direct PL imaging enables the differentiation of series resistance related defect types, if current is extracted from the module during the measurement, which can be achieved in practice by setting the electrical operating point via the inverter or optically via strategic shading of several PV modules in a module string. For example, a distinct contrast appears around a cell area that is electrically isolated by a microcrack (Figure 3), an image feature that allows unambiguous defect classification.

3 | CONCLUSIONS

Direct PL imaging of fielded PV modules under daylight enables the acquisition of high-resolution PL images under direct sunlight excitation using a single camera shot. The technique relies on blocking of sunlight by atmospheric water vapour absorption, resulting in almost complete darkness on the Earth’s surface within an ultranarrow spectral range. By coincidence, the room temperature spectral emission peak from crystalline silicon overlaps with that same atmospheric absorption band. A highly customised spectrally matched UNBPF in conjunction with a telecentric lens arrangement enables image acquisition on industrial modules with PL contributing >90% to the detected camera signal. The technique has substantial potential to be applied in high-volume routine inspection of field-deployed solar modules in utility-scale solar power plants, a role that will become increasingly important in a future where energy supply is likely to be dominated by solar PV power plants.

4 | EXPERIMENTAL DETAILS

4.1 | Irradiance and PL spectra

AM0 and AM1.5 spectral irradiance data are from ASTM E-490 and ASTM G-173 standards, respectively. The c-Si PL spectrum was measured on 29 April 2021 at 12:45 PM in Sydney with a Nirquest Ocean Optics InGaAs spectrometer by taking the difference spectrum between OC and short-circuit (SC) conditions of the HJT module; for scaling purpose, the solar spectrum was measured with the same setup. The spectrum was corrected for the spectral instrument response using a spectrally calibrated halogen lamp.

4.2 | Water vapour data and filter performance calculation

Water vapour absorption line data were extracted from the HITRAN database selecting the more naturally abundant isotope, while the high-resolution atmospheric transmittance spectra were calculated using the ATRAN code. Water vapour maps were computed from monthly averaged Moderate Resolution Imaging Spectroradiometer (MODIS, NASA) satellite-based data from January 2003 to November 2019. For time ratio maps the AM was calculated as

$$\text{AM} = \left( \cos \beta + 0.15 (93.885 - \beta)^{-1.253} \right)^{1/15}$$

with the solar zenith angle $\beta$ in degrees, computed using the PSA algorithm. The effective WVC rises at sunrise and sunset, due to increased AM, but those periods are not relevant for outdoor inspection due to much reduced sunlight irradiance. For the time ratio calculation, presented in Figure S1a, we considered only the times for which AM < 3. For the PL fraction calculation presented in Figure S1c,d, the sunlight contribution is calculated as the integral of the product of the AM0 irradiance and the atmosphere and UNBPF transmittance, while the PL contribution is calculated as the integral of the product of the PL irradiance and UNBPF transmittance. To account for sunlight scattering and reflectance on the module, the PL irradiance is scaled to get an 8% PL component when using a 1,137.5 × 25-nm bandpass filter, as measured for the investigated PERC module with 686 mV/cell OC voltage. The calculation neglects PL absorption, spectral features in the module reflectance, influence of the lens assembly, additional filters and straylight. The filter transmittance profile wings are the one from the design filter transmittance shown in Figure S1b.

4.3 | Filter verification

The UNBPF transmittance $T_f$ was measured at standard temperature and pressure (STP) by the filter manufacturer using a fully calibrated Agilent Cary spectrophotometer. The effective refractive index $n_{eff}$ and centre wavelength $\lambda_{CW}$ measurement versus temperature $T$ were carried out by mounting the UNBPF in a custom temperature-controlled lens tube connected to a 50-mm focal imaging lens fitted to an InGaAs camera (Xenics, Xeva XC137) and imaging a uniform white target in full daylight. Ring patterns in the resulting images (Figure S2a) are caused by the blue shift of the filter transmittance with AOI, as the passband shifts through transmission or absorption bands, respectively, which causes an angle dependent radial intensity profile $I(\theta, T)$. The radial profile of the pattern is given as follows:

$$I(\theta, T) \propto \int_0^\infty T_\alpha(\lambda) T_f(\lambda) \left( \frac{1}{\lambda} \left( \frac{\cos \theta}{\sin \theta} \right)^2 + \Delta \lambda_{CW}(T) \right) d\lambda,$$

with $\Delta \lambda_{CW}(T) = \lambda_{CW}(T) - 1,334.98$ nm, the shift in centre wavelength from the measured transmittance spectrum at STP. Both $\lambda_{CW}$ and $n_{eff}$ were adjusted to fit $I(\theta)$ for each temperature (Figure S2b–d). For $T_\alpha$, an effective WVC of 3 cm was assumed.

4.4 | PV module samples

The two modules investigated here are using monocrystalline half cut cells. Both the HJT (REC Alpha–370 W) and the PERC (LONGI Hi-MO 4–435 W) modules were commercially purchased. The PERC
module is representative of mass manufactured industrial crystalline silicon modules today. Defects were intentionally induced on both modules by mechanical stressing of the module rear, while live EL imaging was used to control the extend of the defects.

4.5 | Direct PL imaging

For outdoor direct PL image acquisition, the same InGaAs camera was used with a customised telecentric camera lens system. The camera sensor temperature was set to −57°C. The telecentric lens system consisted of two identical duplet lenses of focal length \( f = 74.3 \) mm at 1,135-nm wavelength, an adjustable aperture set to 5.07-mm diameter and an industrial 50-mm focal length lens with near infrared anti-reflection coating. Additional 1,000-nm longpass and 1,400-nm shortpass filters were placed in front of the telecentric system to prevent spurious PL signal from the filter-lens system and to further reduce straylight. During the outdoor experiments, the temperature of the filter housing was found to be 35°C due to direct sunlight heating. The temperature-controlled lens tube allowed keeping the filter itself within the desired operating temperature range. The integration time of the camera was kept at 1 s for all experiments, with repetitive averaging used for longer exposure times. All images were corrected for sensor non-uniformity (done at camera level), averaged and then dark corrected (see Figure S3 for images before further filtering). Outliers (faulty pixels in this particular camera model) were removed, then perspective correction was applied. Images were convoluted with a

\[
\begin{pmatrix}
1 & -1 & -1 \\
-1 & 48 & -1 \\
-1 & -1 & -1 \\
\end{pmatrix}
\]

kernel and flat field corrected using a parabolic profile fit.

PL images were acquired under OC conditions, under SC conditions and with a controlled current being extracted using a programmable load that was set to constant current for the investigation of resistance effects. Data presented in Figure 2 and Figure 3 were acquired on the UNSW campus in Sydney on 5 March 2021 from 1:19 PM to 3:25 PM and on 15 March 2021 from 12:17 PM to 12:40 PM, respectively. The WVC on those dates was 2.16 and 2.27 cm respectively. The WVC \( f \) of the filter housing was found to be 35°C due to direct sunlight heating. The temperature-controlled lens tube allowed keeping the filter itself within the desired operating temperature range. The integration time of the camera was kept at 1 s for all experiments, with repetitive averaging used for longer exposure times. All images were corrected for sensor non-uniformity (done at camera level), averaged and then dark corrected (see Figure S3 for images before further filtering). Outliers (faulty pixels in this particular camera model) were removed, then perspective correction was applied. Images were convoluted with a

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