# OPTICAL STRAIN AND TEMPERATURE SENSING WITHIN PHOTOVOLTAIC LAMINATES

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**Summary**
Quantifying the lifetime of photovoltaic modules is getting increasingly important with the aim to drive further technological developments, to reduce financial risks and to accelerate the deployment for new photovoltaic applications. Many lifetime limiting factors can be directly or indirect related to temperature and strain acting on the laminate constituents. In this work a novel optical sensing solution is proposed based on Fibre Bragg Grating sensors which enables a direct validation of the thermo-mechanical strain within a PV laminate. A combined sensor package enables a direct monitoring or validation of the thermo-mechanical stress of a PV cell during production, accelerated testing and field testing. Initial testing shows a high potential due to the non-invasive nature, high sensitivity, scalability and optical transparency.

Keywords: thermo-mechanical, Fibre Bragg Grating, in-situ, photovoltaic, modules,

## 1 Introduction

The lifetime and reliability of Photovoltaic (PV) modules or systems should always be warranted. However, as new module technologies or materials are employed or new applications such as vehicle and building integration are explored, establishing a representative lifetime can become challenging. There are various factors which influence the reliability of PV modules ranging from production-induced stress such as firing or annealing of the metal contacts on the cell, soldering of the cells into strings, lamination of the cells into a module, up to stress induced in the field due to module interactions with the environment (temperature fluctuations, irradiance fluctuations, hail, wind and snow deformations). The various degradation mechanisms, failure modes and their respective impact are generally investigated through a combination of field testing, accelerated aging tests, controlled lab experimentation and simulation. Each variation of testing utilizes specific characterization tools to quantify results.

Field testing largely relies on intermittent characterization using IR imaging, EL-imaging combined with I/V-tracing or power monitoring and visual inspections. As many degradation modes are linked to temperature (module or cell temperatures) thermocouples and PT100's are often used by either laminating them into or attaching them onto the PV module. Although integrating these sensors can be quite invasive on the laminate, continuous thermal monitoring of PV modules is essential as validation or input for simulations (refs).

Standardized stress testing tests such as thermal cycling, according to IEC 61215 and or non-standard combined accelerated stress testing provides a basis for controlled degradation testing [1], [2]. In most cases, similar characterization techniques, as employed during field testing, are used for accelerated stress testing. However, the shorter test-time, controlled conditions and accessibility do allow a more systematic approach to study the performance of various laminate materials and or cell technologies.

During mechanical testing of modules non-contact displacement sensing or 3D scanning [3]–[5] can be used to capture the displacement field of the module. Numerical or analytical simulations can sequentially translate the measured displacements to internal stress and strain levels of the individual constituents. However as argued by , E.H Amalu *et. al.* [6] the accuracy of this approach relies heavily on proper material representation and assumptions used within the models. Advanced characterization methods such as synchrotron X-ray microdiffraction [7], [8] and confocal Raman spectroscopy [9], [10] do allow to directly quantify internal stress and strain levels for small samples. Similarly in-cell sensors have been proposed as an additional tool to directly measure internal cell strain levels and absolute temperatures [11]. In-laminate sensing as the aforementioned technique poses great potential to investigate internal stress and strain values during various loading conditions.

In order to allow for quantization of stressors like strain and temperature on larger scales, physics based simulations are often employed. Simulations pose great potential due to their ability to capture multiple failure mechanisms [12]–[15]. As simulations require assumptions ranging from material models to the abstraction method used, a validation is required. Performing proper validation often proves challenging and in many cases as indicated before rely on indirect measurements.

This work proposes an alternative novel approach to in-laminate sensing which aims to directly quantify thermo-mechanical stress and temperatures during field testing, accelerated stress testing as well as for other lab experimentation. Thereby providing also a valuable tool for the validation of various simulations. This is achieved without the need for adapting any of the laminate constituents and with minimal impact on both the optical and thermo-mechanical behaviour of the module. The proposed sensing solution is optical in nature thereby removing the impact of electromagnetic interference and enabling high accuracy field measurements during operation. Customized optical fibre's containing Fibre Bragg Gratings (FBG) that are integrated into the PV laminate to provide the in-situ thermal and mechanical strain as well the absolute temperature.

## 2 CONVERTING LIGHT TO AN ABSOLUTE CELL TEMPERATURE

Optical fibres have been employed in telecommunication and sensing applications for many years [16]. Although various types of optical sensors exist, FBG-based sensors have been adopted by many industries and its properties captured our interest given their spatial accuracy, optical multiplexing capabilities and commercial availability.

### 2.1 Optical principles

An FBG is created by creating a localized periodic change in the refractive index within the core of an optical fibre. This pattern of alternating refractive indexes referred to as a grating will cause a specific wavelength, named the Bragg wavelength, to be reflected back through the optical fibre as indicated in Figure 1. The transmitted spectrum shows an equal drop in power at the Bragg wavelength allowing sensing both in transmission or reflection. Any strain (thermal or mechanical) exerted to the active part of the fibre will cause a shift in this Bragg wavelength. Its sensitivity for thermal and mechanical strain is mainly determined by the integration method used. The wavelengths used are similar to those used in common telecommunication with typical wavelengths ranging between 1520-1580 nm. These specific wavelengths minimize absorption and scattering effects in single mode fibre thereby maximizing attenuation and thus the noise-to-signal ratio

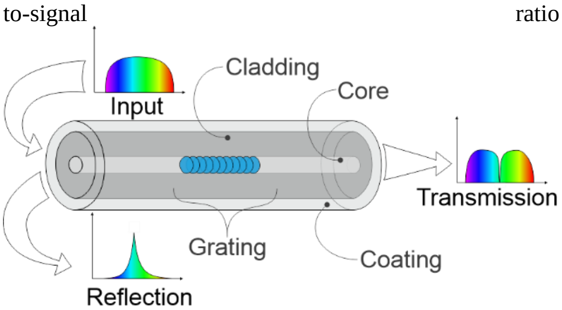


*Figure 1: Operating principle FBG sensor*

### 2.2 Temperature sensing packaging

An FBG is by definition a strain sensor. However, by decoupling the fibre from any mechanical influences only the thermal strain is detected and can be converted to absolute temperatures by characterizing the thermal expansion and thermo-optic properties of the fibre.

Decoupling of the fibre from mechanical strain is achieved by placing the fibre in a capillary tube and fixing it only from one side. This leaves one end of the fibre to expand freely within the capillary. Inside the capillary also a lubricating, high density, transparent liquid sits between the fibre and inner walls of the capillary. As indicated in Figure 2 the ends of the capillary are sealed off using a UV curable adhesive. When exiting the laminate, the thin fibre is protected by a sleeve to prevent breakage during manipulation.

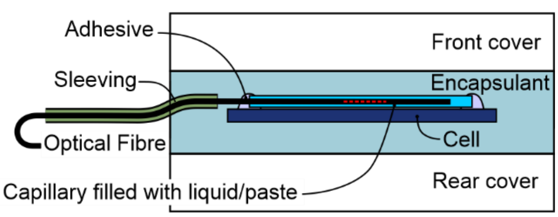


*Figure 2: Temperature sensor integration*

Typical dimensions used for the quartz capillary is an outer diameter between 300-400 µm and an inner diameter between 200-300 µm. As an encapsulant typically has a thickness of 400 µm or above, the capillary will be fully embedded in the capsulation layer. However, the overall bulk of the packaging can be further reduced to about 100-150 µm without any signifcant changes in processing or approach.

As most materials used in the packaging are optically transparant, there was no measurable impact on the EQE when considering a 5mm square area with the sensor packaging positioned in the middle.

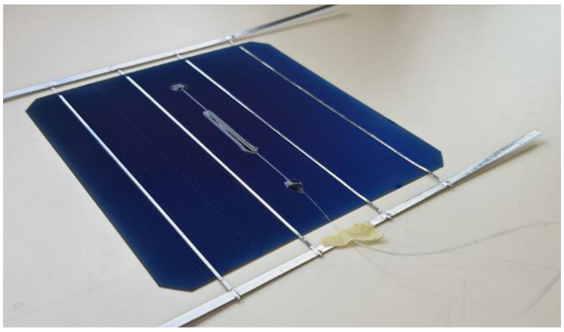

*Figure 3: Temperature sensor integration on to the cell*

### 2.3 Accuracy and sensitivity

In order to demonstrate the accuracy of the sensor a single cell PV laminate was prepared using the structure as referred in Figure 2. The sample was exposed to a cyclic temperature profile ranging from -40 ºC till 80ºC with a steady plateau of at least 30 min at every temperature.

Next the optical parameters were determined based on the stable temperature plateaus in order to translate the measured wavelengths into absolute temperatures. Comparing the temperatures provided by the climate chamber to the ones provided by our sensor a repeatability of ±0.3 ºC was achieved as shown in Figure 4. The limiting factor during calibration was found to be the climate chamber accuracy, thus proving that even better thermal accuracy could be achieved if needed.

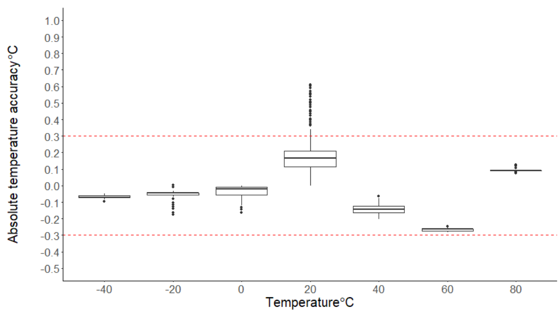


*Figure 4: Absolute temperature accuracy as determined by calibration*

The temperature sensitivity of the packaging was found to about 9.8pm/ºC which provides a relative temperature accuracy of about 0.05ºC using an FBG-scan-904 interrogator.

## 3 THERMOMECHANICAL SENSING

The thermal packaging can be further expanded by including an additional strain fibre next to the temperature sensor as indicated in Figure 5. This allows to decouple mechanical effects from thermal effect which is useful for the validation of various types of simulations. Additional adhesive is applied where the strain sensor is bonded to the cell. The thermo-mechanical sensing package further enhances multiplexing capabilities, as it can be looped throughout the module without the need for additional fibres. With our current setup up to 64 sensing points can be integrated into a single fibre which provides the potential to measure the stress in every cell for an 60 cell module using a single fibre.

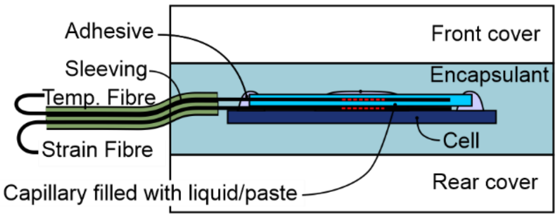


*Figure 5: Thermo-mechanical sensor integration*

## 5 APPLICATIONS

Various PV applications and tests can benefit from this technology. However as the sensing solution is already present during production of the laminate, an obvious application is apply it for process optimization.
In Figure 6, a lamination process is shown for a glass-glass laminate using a polyolefin encapsulant. A lamination temperature of 165ºC was set and also reached.

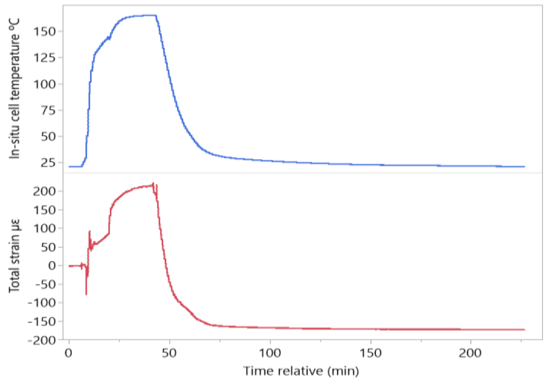


*Figure 6 In-situ temperature and strain development during lamination*

The strain response reveals important steps in the lamination process, such as the placing of the laminate in the laminator (first peak), starting of the lamination process (second peak), start of the pressing stage (sudden increase in temperature) and end of the process (sudden drop in strain). Due to the thermal mass of the sample, the temperature does not decrease immediately. The sample was naturally cooled down to room temperature. Failed lamination recipes also revealed the ability to detect cell cracks during the lamination process. These were also observed as discrete steps in the lamination strain after the process initiated. For the considered encapsulant a final compressive strain of about 170με was measured.

## 6 CONCLUSION and OUTLOOK

An novel in-situ optical thermo-mechanical sensing solution is proposed with a demonstrated accuracy of ±0.3 ºC. The optical transparency of the solution was found to have no significant impact on the optical performance of the module. This show great potential for its use in field applications. The thermo-mechanical packaging was successfully employed to detect various effects occurring during lamination. The technology and packaging is fully scale-able from lab-scale up to field tests. Future work will focus on applying this technology to demonstrators of emerging applications such as infrastructure-integrated PV and building-integrated PV. Furthermore, various failure modes will be investigated using the technology.

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