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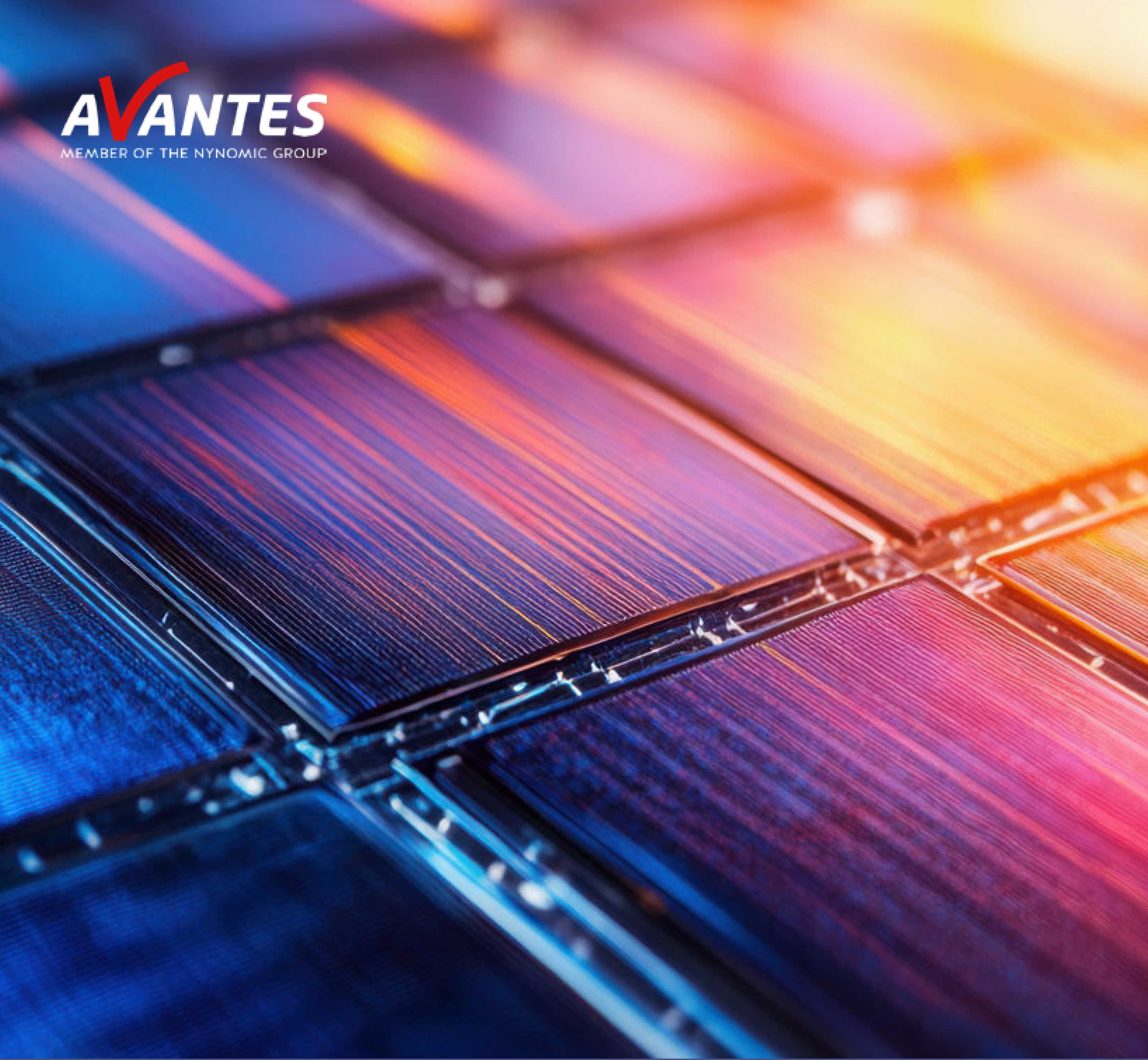
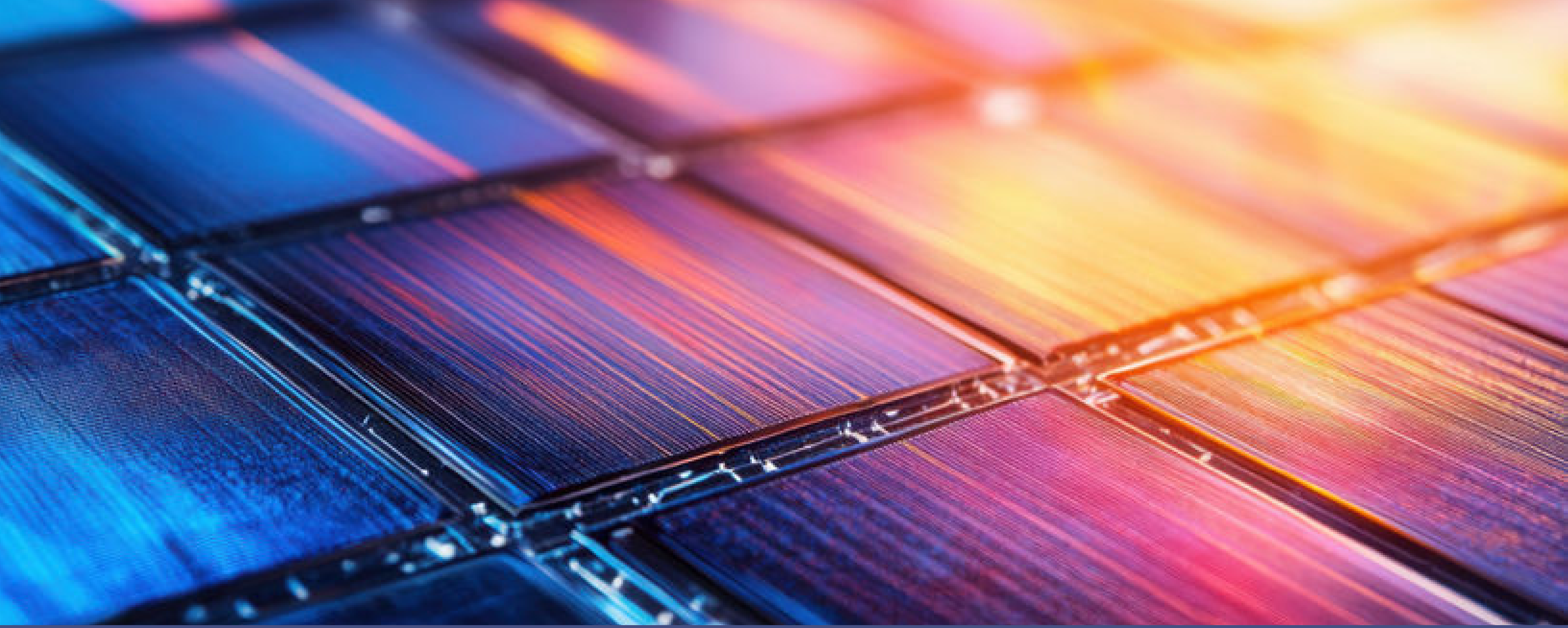


WHITE PAPER

PRECISION IN PEROVSKITE: THE ROLE OF SPECTROSCOPY IN NEXT-GEN PHOTOVOLTAICS



INTRODUCTION

As solar energy takes center stage in the global shift toward renewable power, the demand for high-efficiency, stable, and cost-effective solar panels continues to grow. From traditional silicon-based photovoltaics to next-generation perovskite cells, manufacturers and researchers face the challenge of optimizing performance while ensuring production quality and material reliability. One area that remains under-leveraged in many research and production environments is the added value of spectroscopy.

This white paper explores spectroscopy's role in enhancing solar panel performance, with a focus on perovskite photovoltaics. Drawing from recent academic studies and real-world use cases involving Avantes systems, we examine how spectroscopic techniques enable greater control, stability, and insight across solar cell development.

TABLE OF CONTENT:

1. SPECTROSCOPIC PRECISION DRIVES SOLAR INNOVATION

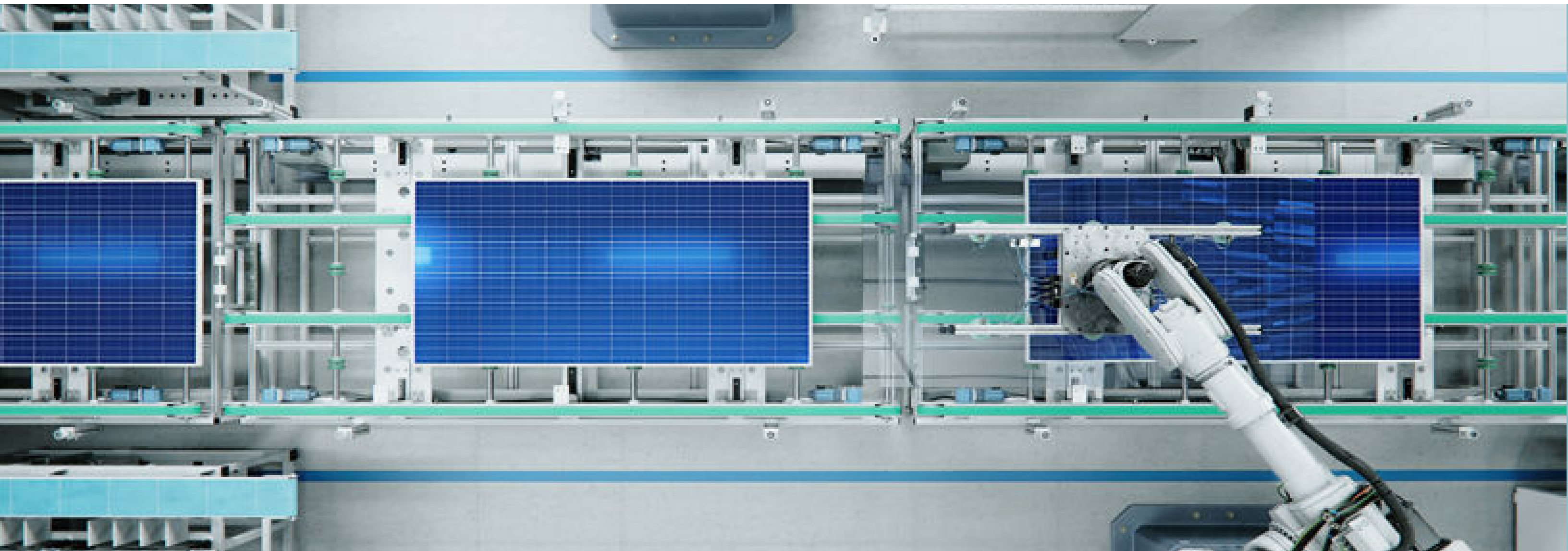
The solar energy industry is experiencing a pivotal transition. Once considered a niche technology, photovoltaics are now a cornerstone of the global renewable energy landscape. According to the International Energy Agency (IEA), solar power will account for nearly a third of the world's electricity generation by 2050.

Photovoltaics (PV) refers to the technology used to convert sunlight directly into electricity using semiconducting materials that exhibit the photovoltaic effect. When exposed to sunlight, these materials generate electric current without any moving parts or fuel combustion. Silicon-based PV cells dominate the market today due to their efficiency, scalability, and long-term reliability. Other technologies, such as thin-film (e.g., CdTe and CIGS), offer advantages in flexibility and material use.

Improvements in conventional silicon-based solar cells have largely driven this growth. Their reliability and steady efficiency gains, commonly exceeding 22% in commercial modules, have made them the backbone of solar energy. Thin-film technologies, such as CdTe and CIGS, have further diversified the market by offering lightweight, flexible alternatives, especially where form factor or cost constraints are critical.

In these established technologies, spectroscopy has long played a key role in optimizing performance. UV-VIS-NIR spectroscopy, for instance, is routinely used to assess absorption and reflectance profiles, helping fine-tune optical bandgaps and layer stacks. Thin-film metrology is essential for maintaining coating uniformity and ensuring anti-reflective and passivation layers perform optimally. Raman spectroscopy aids in identifying mechanical stress and crystallinity in silicon wafers, while Photoluminescence (PL) measurements are used to map carrier lifetimes and detect recombination losses.

In a highly competitive market, even marginal gains in solar cell efficiency can have a significant impact on cost-effectiveness and commercial viability. Spectroscopy enables the level of precision necessary to uncover these gains, providing developers and manufacturers with deep, actionable insights that go beyond what traditional electrical measurements can reveal.



2. THE RISE OF PEROVSKITE PHOTOVOLTAICS

Perovskite solar cells (PSCs) have quickly risen to the forefront of next-generation photovoltaic research due to their remarkable optoelectronic properties. These materials offer tunable band gaps, high absorption coefficients, and low-temperature, solution-based fabrication.

In recent years, research groups, including those at the U.S. National Renewable Energy Laboratory (NREL, have reported power conversion efficiencies (PCEs) above 25% in lab-scale perovskite devices, with certain configurations surpassing 26% under optimized conditions (NREL). These results rival commercial silicon technology's performance and underscore perovskites' commercial viability. Most notably, LONGi (China) achieved a certified 34.85% efficiency for its perovskite–silicon tandem solar cell, setting a world record validated by NREL (PV Magazine).

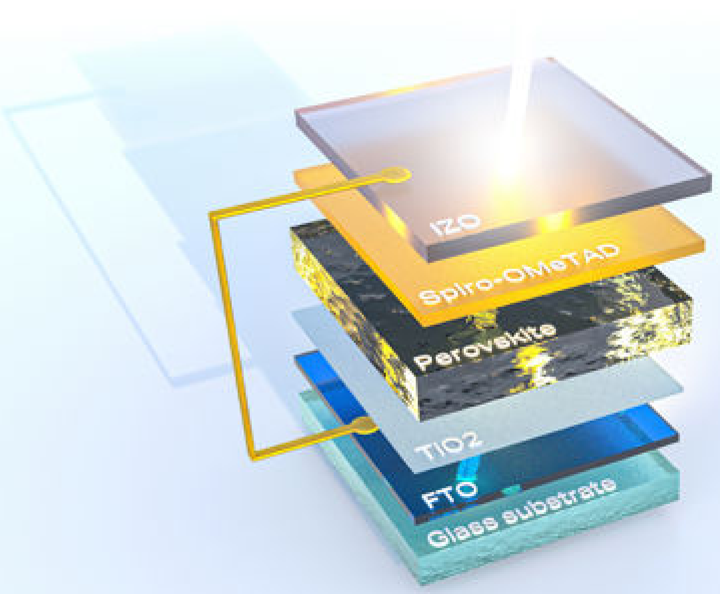
Despite their potential, PSCs face significant challenges:

Material instability: Many perovskite compositions degrade rapidly when exposed to heat, moisture, oxygen, or prolonged illumination.

Reproducibility issues: Variations in crystallization, grain size, and film morphology affect performance consistency.

Scalability challenges: As modules scale up, uniformity across larger surfaces becomes harder to control, often leading to reduced efficiency or shorter lifetimes.

We can conclude that perovskites are powerful but still fragile. Their performance is limited by their sensitivity to environmental and processing conditions, which requires careful monitoring and control. This is where spectroscopy plays an important role, offering real-time, non-destructive analysis to support better material understanding and process reliability.



3. SPECTROSCOPY ADDRESSING PEROVSKITE CHALLENGES

Spectroscopy offers a non-destructive, real-time lens into perovskite materials. Each technique and method provides insight into specific problems associated with instability and variability:

Ensuring Uniformity and Quality in Perovskite Fabrication
Implementing **UV-VIS spectroscopy** will help monitor perovskite layer formation and analyze light absorption behavior, which is critical for tackling the challenge of inconsistent crystallization during fabrication. Variability at this stage can lead to defects, non-uniform optical properties, and ultimately lower device efficiency. By observing how the film develops in real time, UV-VIS spectroscopy enables tighter process control and helps ensure repeatable, high-quality results, one of the key hurdles in scaling up perovskite technology.

The Challenge of Detecting and Reducing Non-Radiative Losses
Photoluminescence (PL) spectroscopy reveals carrier dynamics and helps identify non-radiative recombination losses, which affect overall efficiency. In the context of perovskite solar cells, where material uniformity and defect density vary significantly from batch to batch, PL measurements can expose inconsistencies that would otherwise remain hidden. This makes PL spectroscopy valuable in addressing the challenge of production consistency, offering a non-destructive way to assess material quality before cells are fully fabricated. Additionally, tracking how PL signals evolve under environmental stress contributes to understanding long-term material stability, another challenge in bringing perovskite technology to market.

The Challenge of Quantifying Emission Efficiency
While photoluminescence reveals how light is emitted from excited perovskite materials, **quantum yield (QY)** goes a step further. It measures how efficiently absorbed photons are converted into emitted light. This ratio provides a direct, quantitative measure of non-radiative recombination losses, critical in determining maximum achievable efficiency. Absolute QY measurements, often conducted using an integrating sphere setup, have been performed successfully with Avantes equipment at institutions such as TU Delft, TU Eindhoven, KIT, and TNO. These insights are essential in optimizing materials for improved voltage output and device stability.

Monitoring Thin-Film Consistency During Deposition
Thin-film metrology is particularly useful for monitoring optical thickness and interference patterns, which correlate with film uniformity. In-situ optical thickness monitoring during film fabrication helps identify the onset of phase separation and allows for process adjustments in real time.

Capturing Instability and Degradation Over Time
In-Situ Monitoring: not a technique on its own, but rather a method of applying spectroscopy during active fabrication or stress testing. In-situ monitoring enables real-time tracking of material transitions, such as phase changes or degradation under thermal or light stress.

Each of these techniques and methods contributes to solving a core barrier to scalable, reliable perovskite PV, whether it's catching instability early, quantifying improvement from additives, or improving repeatability from batch to batch.

4. SPECTROSCOPY IN ACTION: USE CASES

The real value of spectroscopy in perovskite development comes into focus when we look at how researchers are applying it to solve specific challenges:

Controlling Crystallization with Reflectance Spectroscopy
In Crystals (2023), reflectance measurements with an **AvaSpec-ULS2048X64 spectrometer** helped researchers monitor thermal annealing in real time, enabling better control over crystallization and improving film uniformity. Resource

In-Situ Spectroscopy for Process Optimization
A 2025 study in Materials employed spectroscopic techniques, specifically real-time monitoring of optical signals, to observe carrier dynamics in perovskite solar cells under pulsed laser excitation. The findings revealed fast photovoltage behavior attributed to free-carrier heating, distinct from the conventional photovoltaic response. They demonstrated how advanced spectral analysis deepens understanding of charge extraction and recombination dynamics. Resource

Defect Detection with PL and Raman
A 2023 review in Communications Materials (Nature) demonstrated how photoluminescence and Raman spectroscopy are used to identify ionic vacancies, trap states, and lattice strain in perovskite films. These defects are closely tied to hysteresis and instability, and the article highlights how spectral mapping techniques help visualize where and how these issues occur, making it possible to guide defect mitigation strategies with greater precision. Resource

Lifetime Gains Through Spectral Feedback
In a 2025 study published in the Journal of Alloys and Compounds, researchers demonstrated that phenyl-functionalized triazatruxene (3P-T) molecules act as an effective passivating agent in tin-based perovskite films, reducing defect sites and improving stability. Resource

Long-Term Degradation Tracked in Real Time
A 2020 study published in Advanced Energy Materials used in-situ photoluminescence and absorption spectroscopy to track halide segregation in perovskite films over a 100-day period. By introducing ethylenediamine (EDA) additives, researchers observed suppressed phase separation and enhanced long-term photostability, providing clear evidence of how spectroscopic techniques can validate material stabilization strategies. Resource

Quantum Yield Characterization of Luminescent Perovskites
A 2023 master's thesis from TU Eindhoven investigated the photophysical stability of luminescent perovskite films, using quantum yield measurements and PL spectroscopy to study degradation effects and emission efficiency. The study made use of Avantes instrumentation for calibrated spectral capture. Resource

5. AVANTES IN PHOTOVOLTAIC INNOVATION

Avantes supports cutting-edge solar research and production with modular, high-performance fiber-optic spectrometers designed for versatility and integration. Our systems are trusted by research labs and production facilities alike and have been featured in multiple peer-reviewed perovskite studies.

Avantes spectrometers are tailored for:

- Real-time UV-VIS-NIR absorption monitoring
- Photoluminescence (PL) and Quantum Yield (QY) characterization with integrating spheres
- Thin-film thickness and interference mapping
- Electroluminescence (EL) detection for device-level validation
- In-line integration in pilot or production environments

Instruments like the AvaSpec-ULS2048XL+, AvaSpec-HERO, and custom multi-channel arrays offer the high sensitivity and speed required for both lab-scale innovation and industrial QC. Our setups are widely used in QY applications across leading research labs in the Netherlands and Europe.

AvaSpec-ULS2048XL+

AvaSpec-HERO

Multi-channel

6. LOOKING AHEAD

As the solar market shifts toward tandem designs and thin-film alternatives, spectroscopy will become not just helpful, but essential. Its ability to reveal hidden inefficiencies, diagnose performance drift, and validate new materials will define the next generation of PV manufacturing.

Spectroscopy bridges the lab and the production line, especially in perovskite development. It turns guesswork into data-driven decisions. For companies working to make perovskite solar cells commercially viable, it provides a clear path to consistency, efficiency, and long-term stability.

Curious to learn more or to try out some of our solutions? Click here to contact us.

RESOURCES

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CONTACT

WE'RE HAPPY TO HELP

Curious how spectroscopy will help you reveal answers by measuring all kinds of material in-line, at your production facility, in a lab, or in the field? Visit our website or contact one of our technical experts.
We are happy to help you!

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