Application Note

Comparisons of IV Curves between Xenon Lamp-Based and LED-Based Solar Simulators

56

Newport
Experience | Solutions

Introduction

Photovoltaic (PV) devices have an essential role in global renewable energy production. Photovoltaic technology can be classified into three types of PV cells:

1) Wafer-based crystalline silicon,
2) Thin filament amorphous silicon, cadmium telluride, or copper indium gallium selenide, and
3) A new generation of organic PV cells (not covered in this application note) (Gangopadhyay et al. (2013))

Currently, PV research is rapidly advancing and diversifying to improve PV cell efficiency, material, and cost. Simultaneously, researchers continue to investigate new and better instrumentation for PV cell characterization.

Advancements in LED technology are providing novel test and measurement equipment to aid research in new PV cells. The new AAA VeraSol from Oriel Instruments is an LED-based solar simulator which offers numerous advantages over previous lamp-based AAA solar simulators. With an equivalent spectral match, irradiance uniformity, and temporal stability, the VeraSol has a filter-free, variable intensity output from 0 to 1 sun. The LEDs are electrically gated and can be turned on or off in less than 100ms without requiring a mechanical shutter for PV IV characterization. The user is granted custom spectral control over the entire AM1.5G spectrum. Functionally, the LEDs have inherently longer lamp lifetime, consume less power, and require less mechanical cooling, which further simplifies the instrument. The lack of additional radiant heat also helps prevent artifacts associated with heating of the PV cells under test. In general, as compared to lamp-based technology, the VeraSol offers a more diverse and equally reliable solar illumination source to characterize and test PV cells.

This application note compares the IV sweep results of a Xenon lamp-based solar simulator to the LED-based Oriel VeraSol solar simulator. In the first section, the spectral outputs of the two simulators are considered.

In the second section, the IV response is compared for a series of PV cells:

- Monocrystalline Silicon
- Polycrystalline Silicon
- Thin Film Amorphous Silicon
- Thin Film Copper Indium Gallium Selenide

Fundamental parameters which characterize an IV curve were generated with ORIEL PVIV software: short circuit current (I_{sc}), Open Circuit Voltage (V_{oc}), Fill Factor (FF), and efficiency (η).

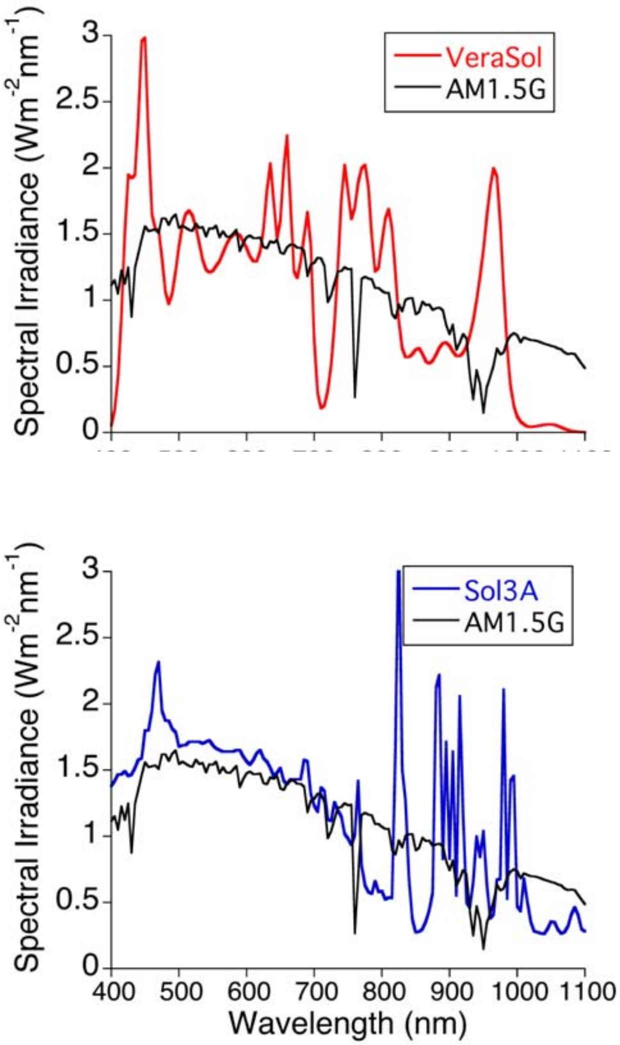
Background

Spectral Match

A solar simulator is designed to mimic light incident from the sun. Three established spectra standards are accepted when matching the irradiance spectrum of the sun with solar simulators: AM0, AM1.5D, and AM1.5G.

AM0 is the irradiance outside of the Earth's atmosphere (zero atmospheres), AM1.5D is the direct component of the irradiance that strikes the Earth's surface, and AM1.5G (global), the most commonly represented spectrum, accounts for both the direct and diffuse radiation striking the Earth's surface. The majority of solar simulators currently rely on Xenon lamp light sources that are optically filtered to match the AM1.5G spectrum. Although this method of simulating the sun has been useful for measuring PV cells, it lacks the ability to adjust the spectral output, has a limited lifetime, and produces a significant amount of heat during test illumination at one sun.

The LED-based VeraSol solar simulator is at the cutting edge of illumination technology. Recent advancements in LED technology have allowed full spectral coverage from 400-1100nm to match the AM1.5G spectrum for Class A, the highest rating for solar simulator spectral match. Comparing the total irradiance of the spectra by integrating from 400-1100 nm, the VeraSol, in fact, provides a closer spectral match to the AM1.5G spectrum than the lamp-based instrument (Figure 1). Using the VeraSol, this match can be further adjusted to compare more accurately to other spectra comparisons or isolate specific spectral regions of interest.



Spectrum	Irradiance (Integral from 400-1100nm)
AM1.5G	756 (W/m2)
VeraSol	760 (W/m2)
Sol3A	818 (W/m2)

Figure 1 – Spectral match of the VeraSol and Sol3A to the AM1.5G spectrum. The table indicates the total irradiance beneath the curve for all three spectra that are the integral spectra over 400-1100 nm.

IV Curve Background

Photovoltaic cells are large PN junctions which generate electricity when the absorption of light provides energy to separate electron hole pairs within a cell. In the absence of light, a PV cell can be modeled as a current source in parallel with a diode. A voltage sweep of a diode with a source meter produces a current/voltage characteristic (IV) in which the current is exponentially related to an applied voltage.

$$I = I_0\left(e^{\frac{qV}{kT}}-1\right)$$

where I_0 is the saturation current of the diode, q is the charge of an electron, k is the Boltzmann constant, T is the temperature, and V is the applied voltage. When light is applied to the PV cell, the IV curve is a superposition of the IV in the dark (diode current) with the light-generated current (photovoltaic current (I_L)); light causes a shift of the IV curve down the y-axis into the fourth quadrant, and the equation becomes

$$I = I_0\left(e^{\frac{qV}{kT}}-1\right)-I_L$$

Plotting the IV curve in the first quadrant (see Figure 3), which is useful for presentation and the determination of a power curve (P=VI), is achieved by simply subtracting the diode current from the photoelectric current (I_L)

$$I = I_L-I_0\left(e^{\frac{qV}{kT}}-1\right)$$
$$I = -I_L + I_0\left(e^{\frac{qV}{kT}}-1\right)$$

Figure 2 represents a simple, equivalent circuit model for a PV cell, which includes the ideal model described above, along with additional series and parallel shunt resistance.

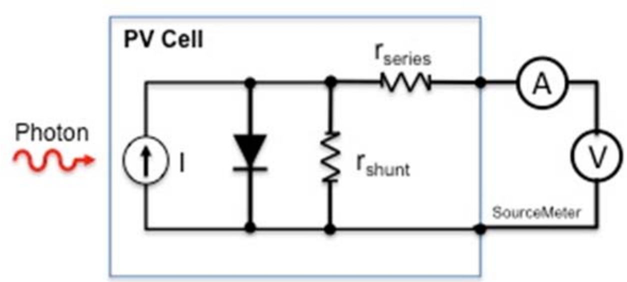


Figure 2– A simple diode circuit model describing a PV cell connected to a source meter for PVIV testing.

The shunt resistance is related to manufacturing defects which can increase the rate of recombination or junction shorting, both of which reduce optimal current flow through the solar cell. The Series Resistance (R_{series}) is related to the ability of current to move through layers of the solar cell and is thus dominated by resistances associated with the semiconductor layers, metal/silicon contacts, and metal on the front and rear surfaces. The following equation adds both the series and shunt resistances into the diode equation above.

$$I = I_L - I_0\left(e^{\frac{q(V+IR_{series})}{kT}} - 1\right) - \frac{V}{R_{shunt}}$$

Although more exact models can better describe the PV cell's IV characteristic, this model incorporates the main components necessary for an initial characterization. Useful information about internal resistances and operating parameters can be attained from both dark sweep and light stimulated IV curves.

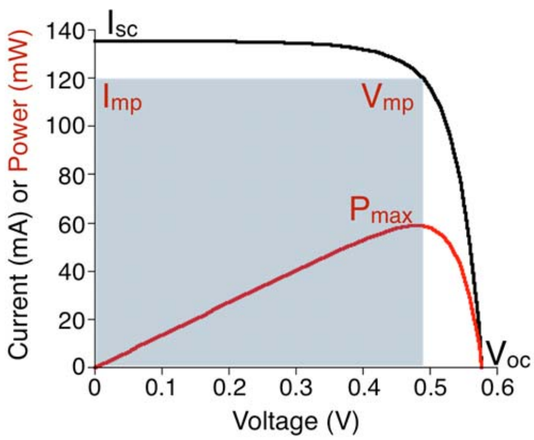


Figure 3 – A sample IV curve taken from a monocrystalline silicon PV cell (4 cm^2) using the Oriel PVIV Kit.

In dark sweep experiments, an external voltage supplies the necessary energy to create electron hole pairs which originate from the flow of current between the metal contacts and the solar cell. This emulates a diode response. In light stimulated experiments, light supplies additional energy to create electron hole pairs within the cell. This results in an additional current (I_L) flow out of the solar cell through metal contacts. The dark sweep IV inherently has less noise because of small fluctuations in light intensity. Because all the current originates from the metal contacts, as opposed to through the entire wafer during illumination, the estimates of series resistance are often lower for dark sweep experiments. In both experiments, the slope of the curve at low voltages (near I_{sc}) estimates the shunt resistances, and the slope at higher voltages (near V_{oc}) estimates the series resistance. The IVs can be plotted on a semi log plot to separate more clearly these two distinct regions in the waveform. In general, the dark sweep IV and the light stimulated IV offer similar information about the diode properties of the solar cell.

The PV cell efficiency (η), which is the ratio of power output of a PV cell to the incident light power (Pout/Pin), is the most widely accepted and fundamental value used to characterize a PV cell. It can be calculated from four parameters, which are determined from a single light stimulated IV curve: the open circuit voltage (V_{oc}), the short circuit current (I_{sc}), the voltage at maximum power (V_{mp}), and the current at maximum power (I_{mp}) (shown graphically, Figure 3). V_{oc} and I_{sc} are the maximum voltage and current achieved by a solar cell and are defined by the intercepts on the x and y-axis, respectively. At both of these operating points the power produced by the solar cell is zero (Figure 3). The current (I_{mp}) and voltage (V_{mp}) at the maximum power point define the characteristic resistance (R_{ch}) and the optimal operating conditions for a solar cell; this represents the maximum power possibly generated by a PV cell. The fill factor (FF), known as "squareness" of an IV curve, is the ratio of the rectangular area (V_{mp} x I_{mp}) from the maximum power point to the rectangular area produced by V_{oc} x I_{sc}. Finally, the efficiency is the ratio of the maximum power output to the input power produced by the light source, scaled to the area of the cell under test.

Measurement Setup

The standard test conditions (STC) for characterizing the efficiency of a PV cell require that measurements are made at a spectral match of AM1.5G, at an intensity of 1 sun (1000 W/m^2), and at a temperature of 25 °C. The spectral match, uniformity of irradiance, and temporal stability of the irradiance are used to grade the performance of commercial solar simulators. The solar simulator designation AAA gives the highest rating of A to all three: spectral match, uniformity and stability.

In this application, the Xenon lamp-based Oriel Sol3A Class AAA and the LED-based VeraSol Class AAA were used to match the AM1.5G spectrum. Both devices are optimized to emit light at the required one sun, and both allow for a range of intensities from 0.1-1.0 suns. Additionally, samples are maintained at 25 °C ± 1 °C. Temperature is often a major concern with lamp-based solar simulators due to the heat from the lamp on the sample, but it is less of a concern for LED based simulators due to the low heat produced from LEDs. The temperature of the device under test (DUT) can be controlled by a temperature-regulated stage in which AM1.5G light can be equilibrated before the IV experiment is performed. Additionally, it can be useful to scan the DUT from V_{oc} to I_{sc} due to sensitivity of V_{oc} to temperature.

An Oriel PVIV Kit was used to generate the following IV curves. A Keithley 4240 SourceMeter is included with the kit to source the voltage and measure the resulting current. Four-wire (Kelvin) connections are recommended for PV cell IV curves thus accounting for any resistance associated with connecting leads to the PV cell. Kelvin probes from Accuprobes allow precise and isolated contact of the two inputs to a small PV cell bus bar. In general, the cables throughout the system should be as short as possible to minimize resistive or inductive artifacts associated with the cables.

Results: VeraSol vs. Lamp IVs

IV sweeps were performed on a variety of silicon and thin film solar cells. Multiple curves were taken for each cell, and each time the leads were repositioned to control for any variation in contact with the PV cell. The short circuit currents were matched to compare equivalent light intensities between the two light sources. Efficiency, open circuit voltage and short circuit current were then measured to quantify any detectable differences between the two light sources.

The band gap for silicon is approximately 1127 nm, and monocrystalline silicon PV cells absorb energy over the entire Sol3A and VeraSol spectrum. Although the spectra for the VeraSol and Sol3A are not identical, they match the total irradiance between 400-1100 nm. A calibrated, monocrystalline silicon PV cell (Oriel Part Number: 91150V) was compared by matching the 1 sun short circuit current (135mA) for both light sources (Figure 4).

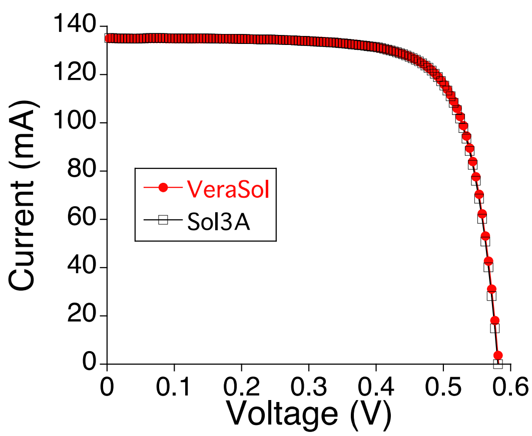


Figure 4 – VeraSol and Sol3A 1 sun IV curves from the calibrated monocrystalline silicon PV cell (number).

The parameter estimates were closely matched and the IV curve essentially overlapped (Figure 4). The following chart compares the efficiency, V_{oc}, and I_{sc} between the Sol3A and VeraSol. The "+/-" indicates the standard error of the mean (sem), indicating the variation in the measurements from the true mean. The VeraSol demonstrates a lower variation about the mean from test to test than does the lamp-based model.

Newport Calibrated Cell

	Efficiency (%)	Voc (V)	Isc (mA)
VeraSol	14.57 ± 0.01	0.5818 ± 0.0001	135.00 ± 0.04
Sol3A	14.67 ± 0.04	0.5810 ± 0.0004	135.00 ± 0.13

Comparable results were obtained for monocrystalline silicon nitride AR coated PV cells, textured/glass covered silicon nitride PV cells, as well as a multicrystalline PV cell.

cSi-Silicon Nitride AR Coating

	Efficiency (%)	Voc (V)	Isc (mA)
VeraSol	15.26 ± 0.004	0.613 ± 0.0004	180.05 ± 0.10
Sol3A	15.20 ± 0.084	0.608 ± 0.0005	180.02 ± 0.05

cSI-Glass / Silicon Nitride AR

	Efficiency (%)	Voc (V)	Isc (mA)
VeraSol	12.54 ± 0.09	0.583 ± 0.0001	406.38 ± 0.12
Sol3A	12.53 ± 0.38	0.578 ± 0.0005	407.24 ± 0.13

Multicrystaline Si

	Efficiency (%)	Voc (V)	Isc (mA)
VeraSol	9.47 ± 0.077	0.602 ± 0.0005	252.4 ± 0.2
Sol3A	9.59 ± 0.110	0.598 ± 0.0007	252.8 ± 0.5

This similarity in IV curve response for silicon was expected, considering the wide band gap for silicon and the spectral match between 400-1100 for the VeraSol and Sol3A.

To test further the consistency between these two light sources, two thin film PV cells, a copper indium gallium selenide (CIGS) and an amorphous silicon module were chosen with band gaps at approximately 1133 nm and 730 nm, respectively (Figure 5a and 5b).

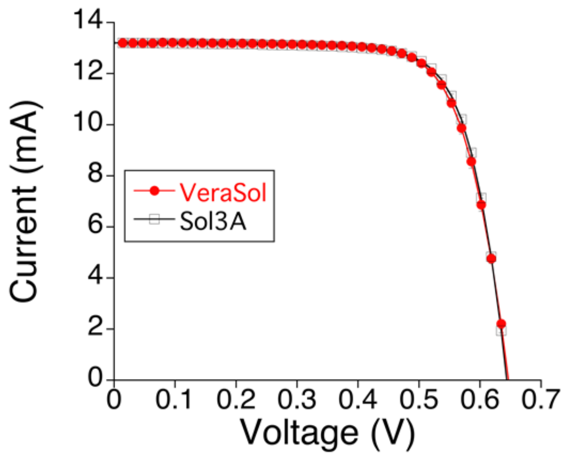


Figure 5a – VeraSol (red) and Sol3A (black) 1.0 sun IV curves from Copper indium gallium thin film PV cell (0.42 cm^2).

Thin Film CIGS

	Efficiency (%)	Voc (V)	Isc (mA)
VeraSol	14.63 + 0.04	0.642 + 0.0005	13.10 + 0.01
Sol3A	14.62 + 0.08	0.639 + 0.0002	13.10 + 0.01

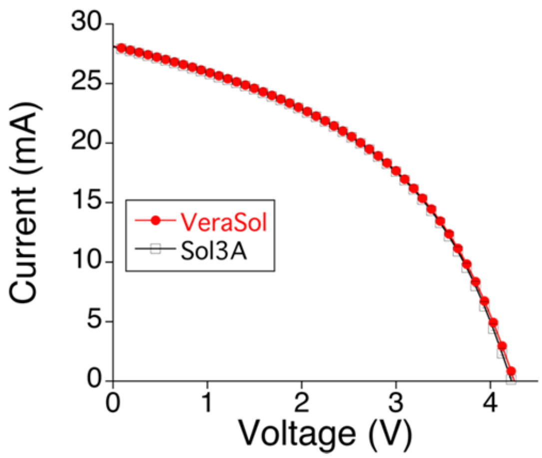


Figure 5b – VeraSol (red) and Sol3A (black) 1.0 sun IV curves from an amorphous silicon thin film module (6.75 cm^2).

Thin Film amorphous Si Module

	Efficiency (%)	Voc (V)	Isc (mA)
VeraSol	2.705 + 0.001	4.243 + 0.004	28.16 + 0.02
Sol3A	2.700 + 0.002	4.216 + 0.007	28.09 + 0.04

Similar to the results from the crystalline silicon test, both PV cells produced almost identical IV curves and resulting parameters when comparing the VeraSol to the Sol3A. Although it is possible that results using other materials may reveal a difference between the two light sources, we did not detect a significant difference in these tests.

Temperature: VeraSol vs. Lamp IVs

Intrinsically, the VeraSol includes a unique feature by preventing extensive heat from altering the PV cell under test. This is a desired quality for certain research questions. Solar radiation beyond the band gaps of a material generates heat, and this heat has the additional effect of shifting the open circuit voltage of the IV curve. As shown in Figure 6, IV curves generated over a 30 minute, continuous one sun illumination do not shift with the VeraSol solar simulator (Figure 6A). In contrast, the lamp-based simulator causes a left shift in IV curve within less than one minute (Figure 6B). The corresponding temperature change of the silicon PV wafer is illustrated in Figure 6C. Due to the LED design of the VeraSol, neither high energy light (less than 400nm) nor far-reaching infrared light (greater than 1100nm) contribute to the heating of the sample. For narrow band gap materials, the VeraSol can further limit this heating by excluding individual unwanted wavelengths.

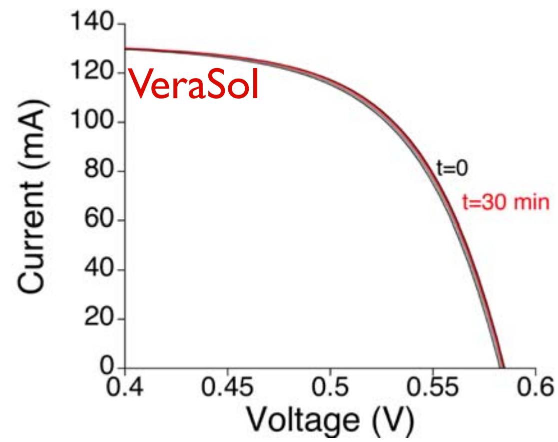


Figure 6A – IV Curves taken at 1, 3, 10, 15, 20, 30 minutes under continuous 1 sun illumination.

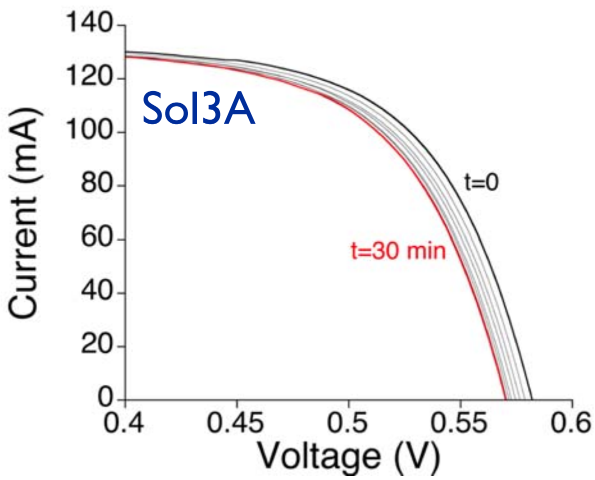


Figure 6b - IV Curves taken at 1, 3, 10, 15, 20, 30 minutes under continuous 1 sun illumination.

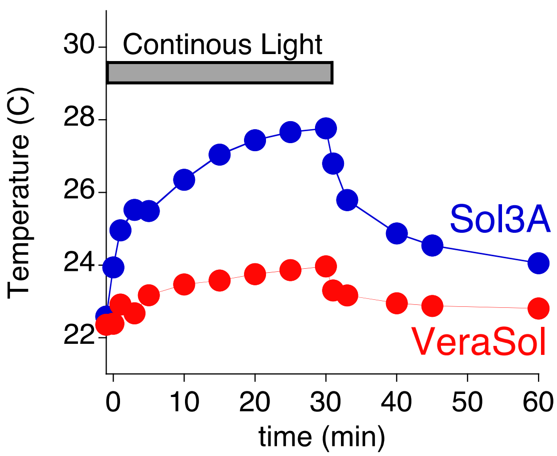


Figure 6c - PV cell temperature for the two experiments in A and B over the 30 minute light exposure as well as a 30 minute recovery with no light.

Conclusion

The spectral differences between the VeraSol and the Sol3A did not affect the IV curve response for the PV cells tested. Apart from the close similarity in IV curve responses, the VeraSol often produced a more reproducible IV curve from measurement to measurement as is evident from a lower standard error of the mean values. LED-based technology is likely to produce a lower overall variance in spectral irradiance, potentially providing the more consistent results. Further study would quantify this effect.

Improved consistency, combined with lower light source heat generation and isolated spectral control, promote the LED-based VeraSol as improved solar simulator technology over the previous generations of lamp-based technologies.

References

"Global Market Outlook for Photovoltaics 2014-2018". www.eipa.org. EPIA – European Photovoltaic Industry Association. Archived from the original on 12 June 2014. Retrieved 12 June 2014.

Gangopadhyay U, Jana S, Das S (2013) State of Art of Solar Photovoltaic Technology. *Conference Papers in Science* 2013:e764132.

Bowden, S and Honsberg, C, *PV Education, 2014. http://pveducation.org/pvcdrom, electronic book.*

This application note was written by Gregory P. Leary, ILX Lightwave.

For application assistance or additional information on our products or services you can contact us at:

Oriel PV Instruments – A Newport Company
31950 Frontage Road, Bozeman, MT 59715
Phone: 406-556-2481 • 800-459-9459 • Fax: 406-586-9405
Email: OrielPV.sales@newport.com

To obtain contact information for our international distributors and product repair centers or for fast access to product information, technical support, LabVIEW® drivers, and our comprehensive library of technical and application information, visit our website at: **www.newport.com/oriel**

ORIEL® INSTRUMENTS
A Newport Company