Novel Laser Power Sensor Improves Process Control

A dramatic technological advancement from Coherent has yielded a completely new type of fast response power detector. The high response speed is particularly advantageous in commercial applications where it enables CW laser power to be sampled faster and more frequently; with modulated sources it delivers peak power and temporal pulse shape data, from which pulse energy can be derived. This real-time feedback can be used to improve laser system throughput and quality, and to improve process precision, with minimal engineering investment.

Introduction and Overview

Lasers are used to process materials in an extraordinarily diverse array of applications – in industries such as semiconductor electronics, medical product manufacturing, consumer product packaging and automotive production. While these uses involve numerous different laser technologies working with many different materials, they often share a common requirement. Namely, the need to regularly measure laser output characteristics such as power, pulse energy, pulse shape or beam profile to ensure optimum and consistent processing. Furthermore, this need for accurate laser characterization is becoming more critical today due to two overarching trends occurring simultaneously in many different industries. The first of these is a growing requirement for increased process precision, and the second is a drive to reduce production costs. This document reviews a new laser power measurement technology specifically designed for use in laser-based processing tools, which directly addresses these needs.

Measurement Requirements

For most laser processes, regardless of the operating regime (millisecond, nanosecond or femtosecond) or output wavelength, average power is a critical parameter since it usually directly affects material removal or transformation rates. And for many applications, the actual laser power delivered to the work surface is subject to fluctuations since it can be impacted by a number of different factors. These include inherent variations in laser output, as well as changes in optical alignment within a beam delivery system, and degradation in the performance of individual beam delivery optics (such as a drop in reflectivity on a mirror).

Pulse shape is also an important parameter, particularly for applications in the thermal processing regime that commonly utilize modulated CO_2 lasers. Relatively small changes in the modulated pulses can affect process results such as cut edge quality or hole shape. Laser variations can make a process difficult to control, or may require the process to be slowed down to achieve the precision required.

A general move in industry towards higher process precision or increased throughput typically narrows the process window, making it more intolerant of any changes in either delivered laser power or pulse shape. The narrower this window gets, the more frequent the need to measure laser output characteristics to verify that it remains within acceptable bounds. Real-time pulse shape monitoring (which can be used to monitor peak power and calculate pulse energy) can provide a feedback loop back to the laser, which translates into improved process speed and feature uniformity.

The frequency of laser measurement also strongly impacts costs because it enables quicker identification of production problems. Specifically, it can identify nascent problems, or problems that have just occurred, and therefore prevent the fabrication of poor quality parts before they move down the line and become expensive scrap or rework.

Given the benefits of frequent laser power monitoring, why isn't this simply common practice in most industries? The answer is that the power measurement technology currently employed for many laser types is relatively slow, and thus, can't keep pace with the speed of the production line. As a result, laser power is measured only intermittently in order to minimize stopping or slowing of production; and due to limitations of photodiodes, pulse shape monitoring is rarely employed.

Traditional Laser Power Sensors

There are two dominant technologies in use for measuring the average power of lasers. These are thermopiles and semiconductor photodiodes.

Thermopiles have been used for many years as the detector of choice for high power lasers. These detectors operate on the thermoelectric principle in which thermal energy is converted into electrical energy. The typical thermopile consists of a central light absorbing disk, a series of thermocouples that surround this disk, and an annular heat sink around the ring of thermocouples (Figure 1).

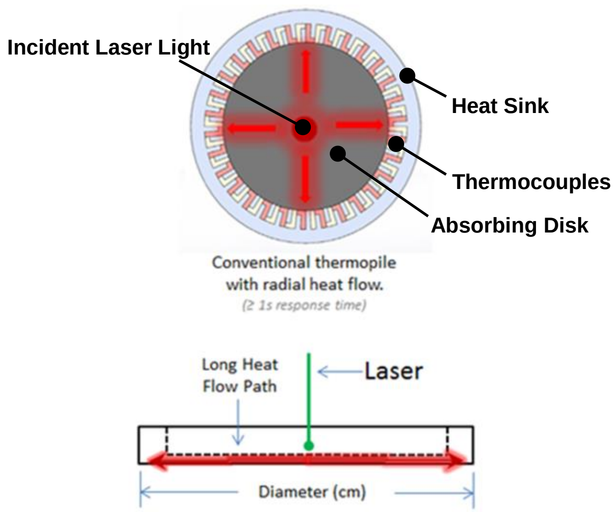

Figure 1
Construction of a Traditional Thermopile

In operation, incident laser energy falls on the absorbing disk in the center of the detector and is converted into heat. This disk is typically coated with a material that absorbs light over a very broad wavelength range in order to enhance sensitivity. The heat then flows across the width of the thermopile disk to the heat sink which is held at a near constant ambient temperature by either air- or water-cooling. The temperature difference between the absorber and heat sink is converted into an electrical signal by the thermocouples. Calibrated electronics in the meter convert this electrical signal into a laser power reading.

Thermopile sensors have several advantages, including an extremely broad spectral range, an ability to work over a wide range of input powers, high laser damage resistance, and uniform spatial response (meaning insensitivity to changes in beam size, position or uniformity). The limitation of the technology is that the transfer of heat across the width of the thermopile disk makes this technology inherently slow. Specifically, it often takes several seconds before the heat flow induced by the laser reaches equilibrium, and the power measurement becomes steady on the display. Physically larger sensors take longer to reach this steady state. This slow response time makes thermopiles best suited for measuring CW laser power. For pulsed lasers, the best they can deliver is average power over a finite time interval, or total integrated energy from a long burst of pulses.

Semiconductor photodiodes are essentially a solid-state diode (*pn* junction). Incident laser photons are absorbed by the device and converted into charge carriers (electron and holes). These can be sensed as current or voltage depending upon how the junction is biased.

Photodiodes offer high sensitivity enabling them to detect very low light levels. They saturate approximately 1 mW/cm^2, so attenuating filters must be used when operating at higher powers. Photodiodes have a fast response time and thus can be useful for looking at pulse shapes.

The drawback of photodiodes is that they have smaller active areas, a much more limited spectral range, and lower spatial uniformity than thermal sensors. The latter can affect the measurement repeatability of non-uniform beams or beams that wander over the detector surface between measurements. Several different semiconductor material combinations are available to produce photodiodes that work in the visible, near infrared or far infrared regions. Together, these characteristics make photodiodes most useful for low power measurements of CW lasers, as well as pulse shape characterization of nanosecond pulsed lasers.

PowerMax-Pro Technology

Coherent developed PowerMax-Pro technology (Patent Pending) to meet the growing need for a laser power sensor that offers the broad wavelength sensitivity, large dynamic range and high damage resistance of a thermopile, together with the fast response speed approaching that of a semiconductor photodiode. The PowerMax-Pro is constructed and configured differently than a thermopile. Specifically, in this device the heat flows vertically through the detector, and the electrical field that is generated moves perpendicular to the heat flow (Figure 2).

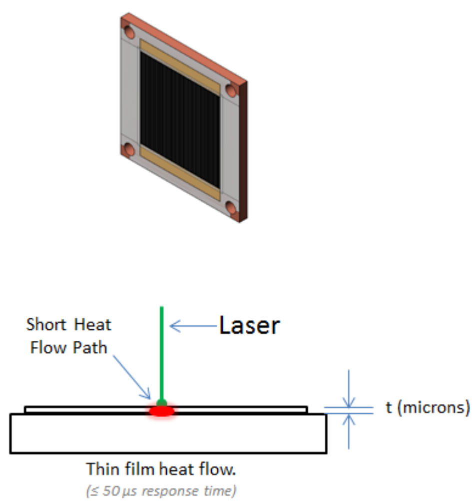

Figure 2
Basic Configuration of a PowerMax-Pro Sensor

The materials used in this sensor are a stack of films which have layer thicknesses on the order of microns. Incident laser light is absorbed and generates heat which is able to flow very quickly through these thin layers to the heat sink below the detector where it is dissipated. The electrical signal from the thin film layers moves laterally to the edges of the device where it can be measured by tapping into the sensor electrodes.

High Speed Measurements

In contrast to the traditional, radial flow thermopile, which has a sensing time constant value of several seconds, the time constant for the thin film configuration is in the microsecond range. This enables the sensor to provide an essentially instant power measurement without any overshoot (Figure 3). The PowerMax-Pro sensor preserves the main benefits of the traditional thermopile architecture, namely large active area (30 mm x 30 mm), wide dynamic range (50 mW to 150W), high damage resistance (14 kW/cm²) and broad wavelength range (300 nm to 11 µm).

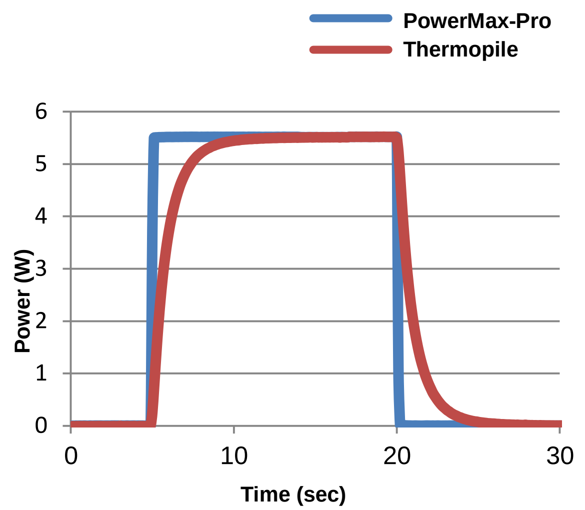

Figure 3
The Rise Time of a Typical Mid-Power Thermopile (30W) Compared with the PowerMax-Pro

The response speed of PowerMax-Pro sensors allows users to move beyond just measuring average power, and enables visualization of the temporal pulse shape and peak power of modulated lasers with pulse lengths greater than 10 µs. These pulses can then be integrated to calculate individual pulse energy. Previously, it was only possible to measure the shapes of CO_2 laser pulses of this duration using mercury cadmium telluride (MCT or HgCdTe) photodiodes. However, these exotic detectors have a number of significant drawbacks. For example, they have a small active area, typically on the order of 1 mm² or even smaller, which makes it impossible to monitor true pulse energy or total output power. Also, photodiodes saturate at very low powers and can be easily damaged if exposed to too much power. Because of these two factors, MCT photodiodes usually only sample a portion of the beam, and are used to monitor for missed pulses, or to check for large changes in relative power output.

Another problem with MCT photodiodes is that their noise level is high, making them unsuitable for accurate peak power and precise pulse energy monitoring. Expensive, multi-stage, thermoelectric coolers may be required to stabilize the baseline noise if these sensors are used to do anything other than detecting missed pulses. Performance at less than 20 kHz, which is common in modulated CO_2 applications, is further compromised due to flicker, or 1/f noise, again making absolute power or energy measurement difficult.

Meter Electronics

A sensor is just part of a measurement system, and can only deliver high quality data if it is matched with electronics to properly acquire, condition and process the raw signal from the sensor. Coherent has developed the LabMax-Pro SSIM laser power meter specifically to fully capitalize on the inherent capabilities of PowerMax-Pro sensors.

To minimize user cost and maximize flexibility, the LabMax-Pro is packaged as a Smart Sensor Interface Module (SSIM) that interfaces with a host computer through either USB or RS-232. LabMax-Pro PC, a new Windows PC application, then enables instrument control and displays measurement results, including laser tuning and pulse shape visualization, on a host computer. The software also performs a wide range of analysis functions such as live statistics, histograms, trending and data logging. In addition, a complete set of host commands can be sent through either the USB or RS-232 interface which is particularly useful for embedded applications.

High Speed Sampling for Pulse Visualization

The standard operating mode of the LabMax-Pro SSIM utilizes a typical 10 Hz sampling rate. At this data rate, it allows PowerMax-Pro sensors to provide an instant power reading, much like a photodiode, but, of course, taking advantage of the sensor's ability to directly read very high powers. High volume processes that use high repetition rate or quasi-CW lasers, such as picosecond and femtosecond lasers, can benefit significantly from fast power measurements. Time currently spent monitoring the process with thermopiles can be spent processing parts, and with such rapid measurements, the process can be monitored more frequently. Instead of spending up to a minute or more taking a reading, the measurement can be performed in less than a second with PowerMax-Pro technology, enabling throughput improvement with very little engineering investment.

The standard operating mode is best used to measure the power of CW lasers, or the average power of high repetition rates lasers. Two High Speed sampling modes have been implemented in the meter electronics and software to fully exploit the rapid response speed of PowerMax-Pro sensors for measuring pulsed lasers operating between these two extremes. These modes enable advanced analysis of high power, pulsed lasers in a way that has never been possible before.

The first High Speed mode utilizes a continuous data sampling rate of 20 kHz, allowing pulse shape analysis of modulated lasers with repetition rates of up to 2 kHz. These types of pulse trains are common in many laser-based medical treatments and some materials processing applications such as micro welding.

The accompanying screen capture shows data gathered using a 20W CO_2 laser to illustrate the type of detail that can be obtained in this mode.

Coherent PowerMax-Pro

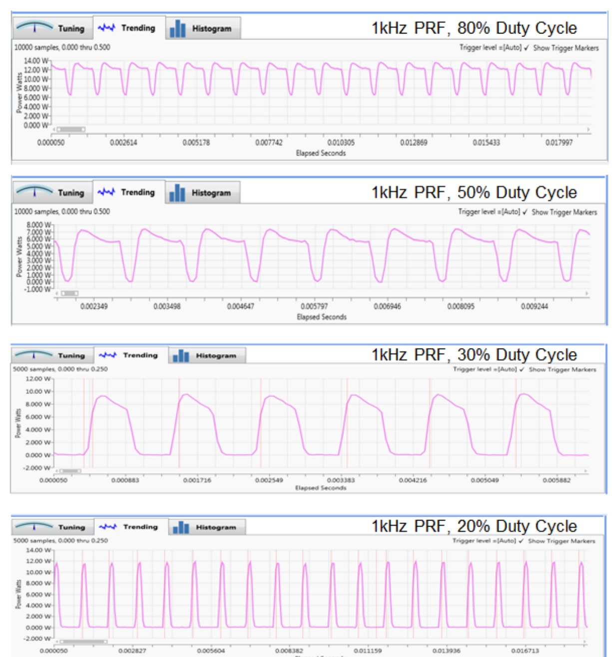

Figure 4
Pulse Shape Visualization Obtained with a PowerMax-Pro Sensor and LabMax-Pro Electronics and Software

The second High Speed mode is called "Snapshot Mode," which provides burst sampling at a rate of 625 kHz for a period of time up to 384 milliseconds. This is fast enough to enable visualization of the pulse shape of the modulated lasers common in various commercial cutting, engraving and drilling applications, as well as long pulses and pulse trains used in aesthetic medical applications. This type of temporal visualization offers new insight into the true performance of the laser previously masked by slow thermopiles. This new information, now available to engineers, removes some of the “magic” involved in setting up materials processing applications. It provides developers with more repeatable methods to transfer processes from engineering to manufacturing and to control and monitor the process once it’s up and running. Many thermal-based materials processing applications can be better controlled with this information, leading to faster processing with higher yield; at the same time, the quality of laser produced features can be enhanced.

The following figures demonstrate the data quality and high pulse shape fidelity that can be achieved.

Modulated 10.6 µm CO_2 Laser

- **10 µs PW**
- **10 kHz PRF**
- **10% Duty Cycle**

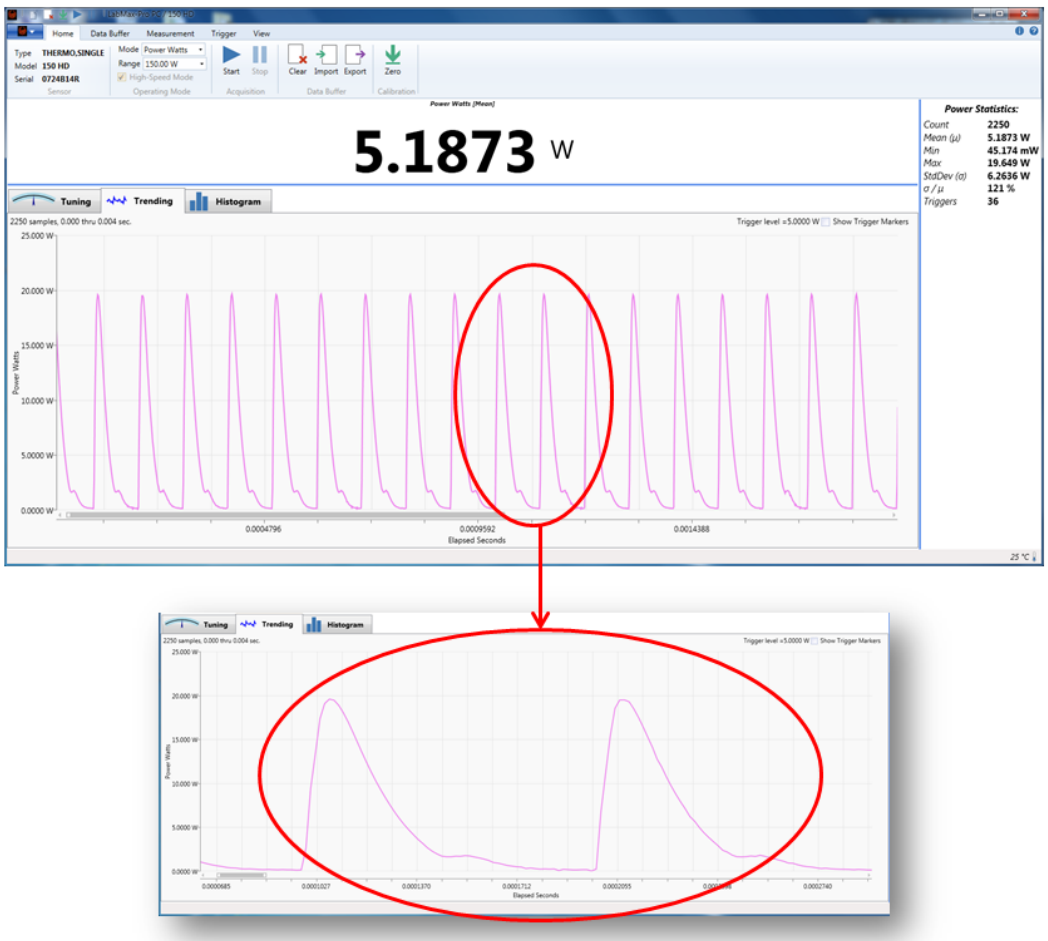

Figure 5
The New LabMax-Pro Offers a “Snapshot Mode” Which Enables Visualization of Pulses as Short as 10 µs and at High Duty Cycles

Modulated 10.6 µm CO_2 Laser

- **50 µs PW**
- **8 kHz PRF**
- **40% Duty Cycle**

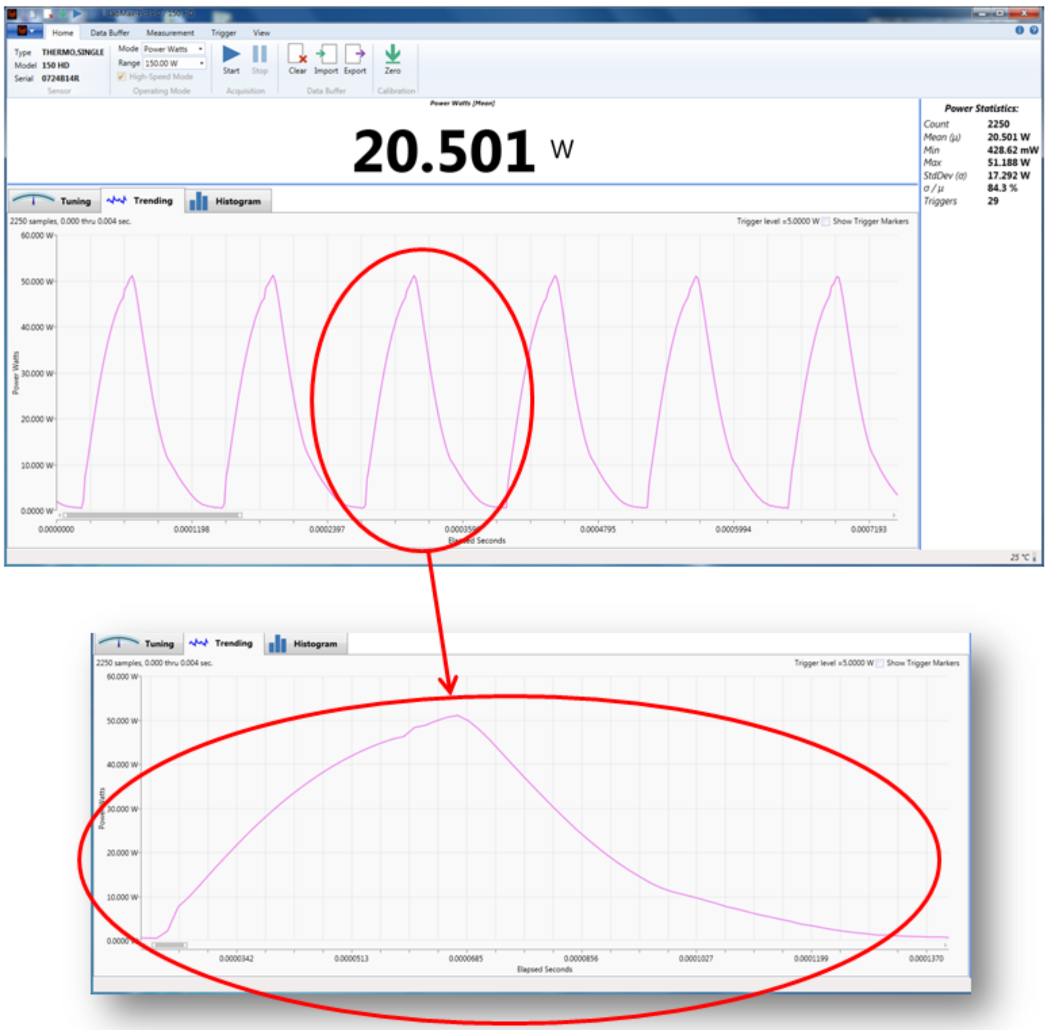

Figure 6
Pulse Shape Visualization Obtained with a PowerMax-Pro Sensor and LabMax-Pro Electronics and Software

Modulated 10.6 µm CO_2 Laser

- **500 µs PW**
- **1 kHz PRF**
- **50% Duty Cycle**

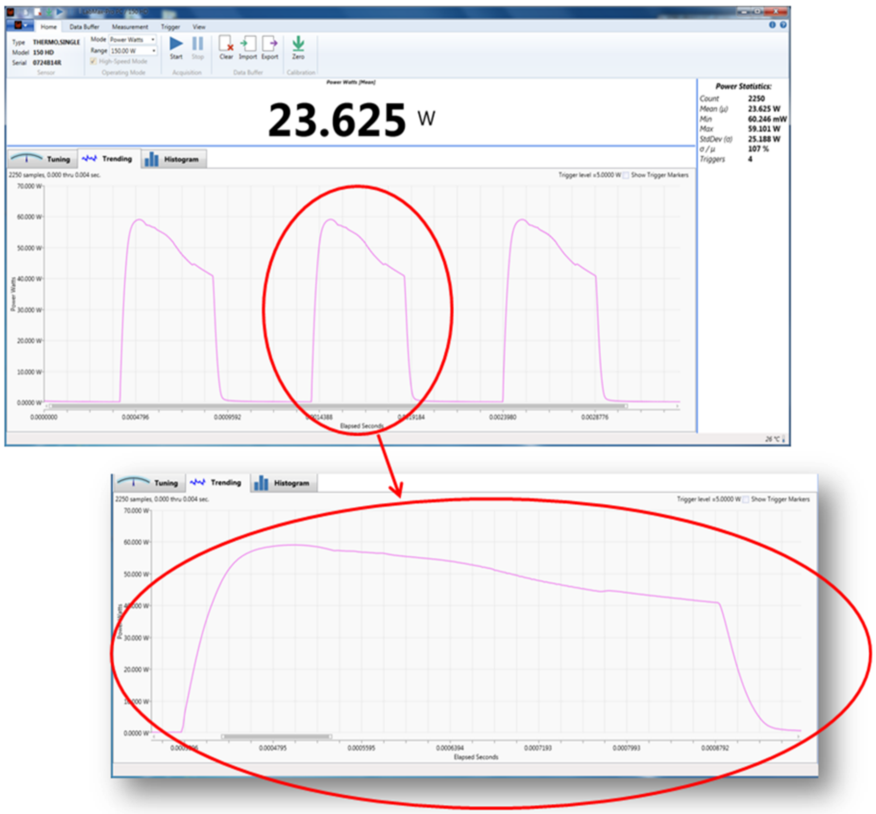

Figure 7
Pulse Shape Visualization Obtained with a PowerMax-Pro Sensor and LabMax-Pro Electronics and Software

Conclusion

In conclusion, traditional laser power sensors have masked some of the instability in lasers by averaging out pulse-to-pulse variation. Additionally, the slow speed of these sensors required a compromise between measuring frequently (to ensure quality) and throughput reduction resulting from time spent taking those measurements. In a major paradigm shift, Coherent's new PowerMax-Pro sensor technology, coupled with our LabMax-Pro hardware and software, have now eliminated that compromise. The result is a laser analysis platform that will deliver several important benefits to users of laser-based processes. These are improved throughput due to increased measurement speed, reduced costs from the reduction of scrap and rework, and higher quality product enabled by quicker feedback on variations in laser power or pulse shape.