Measuring Laser Power and Energy Output

Introduction

The most fundamental method of checking the performance of a laser is to measure its power or energy output. Laser output directly affects a laser's ability to perform a process. Measuring and monitoring this parameter is often very important from the time a laser is first manufactured, through system integration, and on to the final end customer who will be using the laser system in applications as far-ranging as medical, scientific, biomedical, and industrial applications.

There are several key decisions to be made when choosing the right measurement equipment for the job. Just as there are many different types of lasers with widely varying specifications, there are different measurement technologies available that are appropriate for specific types of lasers and matched to particular laser specifications. This paper will discuss the basics of laser power and energy measurement and guide you through the process of selecting the best instrument for the task.

It will be useful to define the terminology used to describe these devices within the photonics industry. These types of measurement systems usually involve two pieces of equipment that are often sold separately: First is a sensor that is placed into the laser beam and provides a signal output proportional to the laser input. The second component is the meter, which is an analysis and display instrument that will interpret the signal from the sensor, apply various analog and digital corrections (such as compensating for the difference between the calibration wavelength and the wavelength of the laser), and then provide a measurement. Some meters provide a measurement that must be viewed on the display, while other meters can provide more sophisticated data analysis and PC interfacing options.

Laser Power & Energy Technical Background

The first thing to take into consideration when shopping for a laser measurement system is the fundamental measurement that is needed – measurement of power or pulse energy.

First, it will be useful to cover what these two measurements are referring to. The power of a laser is measured in Watts (and often reported in terms of nW, mW, W, etc.). This is referring to the optical power output of the laser beam, which is the continuous power output of continuous wave (CW) lasers, or the average power of a pulsed or modulated laser.

The energy of a laser typically refers to the output of a pulsed laser and is related to the power output, where the energy (E) is the laser's peak power (P_{PEAK}) multiplied by the laser pulse duration (t):

$$E = P_{PEAK} \text{ x } t.$$

The average power of a pulsed laser (P_{AVG}) is the pulse energy (E) multiplied by the laser repetition rate (Hz):

$$P_{AVG} = E \text{ x Hz}$$

For example, an Excimer laser might have a 10 ns pulse width, energy of 10 mJ per pulse, and operates at a repetition rate of 10 pulses per second. This laser has a peak power of:

$$P_{PEAK} = 10 \text{ mJ} / 10 \text{ ns} = 1 \text{ MW},$$

and average power of:

$$P_{AVG} = 10 \text{ mJ x } 10 \text{ (1/s)} = 100 \text{ mW}.$$

The pulse length can be very short (i.e. picoseconds or femtoseconds) resulting in very high peak powers with relatively low pulse energy, or can be very long (i.e. milliseconds) resulting in low peak power and high pulse energy, while each of these conditions might have similar average power levels.

Throughout the rest of this paper when laser power is referred to, it is referencing the average power of pulsed lasers, or the power output of CW lasers.

Sensors Used to Measure Laser Power & Energy

Now that the fundamentals of laser power and energy have been covered it will be useful to describe the key types of measurement technologies commonly available in the market for measuring these different types of lasers. The most common measurement technologies are pyroelectric sensors that can only measure pulsed lasers, thermopiles that can measure pulsed or CW lasers, and semiconductor photodiodes (commonly referred to as optical sensors) that are sometimes restricted to CW-only lasers and can sometimes be used with both pulsed and CW lasers, depending upon the intended use.

Technology	Measurement Type
Pyroelectric sensors	• Measures the energy of pulsed lasers and can only work with pulsed lasers • Average power is calculated by measuring laser repetition rate and multiplying by the pulse energy
Thermopile sensors	• Measures CW lasers and integrates energy of pulsed lasers to produce an average power measurement • Can also be used to integrate the energy of a single pulse – most common for measuring energy of millisecond and longer pulse width medical and industrial lasers.
Semiconductor photodiode/Optical	• Most often used for measuring low CW laser power. • Also used in some sensors for measuring low pulse energy, however, may not respond to CW lasers when used in this way.

The image below shows what these sensor technologies typically look like. From left to right the sensors shown are an OP-2 photodiode, LM-45 thermopile, and J-50MB-HE pyroelectric sensor. Also pictured is a LabMax-TOP power and energy meter.

The following section will provide more depth of information about each sensor technology.

Thermopile Sensors

Thermopile sensors are a great all-purpose technology suitable for many lasers. They are used for measuring CW laser power, average power in pulsed lasers, and are often used to integrate the energy of long pulses. Thermopile sensors absorb incident laser radiation and convert it into heat. This heat ultimately flows to a heat sink that is held at ambient temperature by either convection-cooling or water-cooling. The temperature difference between the absorber and the heat sink is converted into an electrical signal by a thermocouple junction.

Thermopiles operate across a wide range of input powers, and unlike a photodiode-based sensor they will not saturate. The spectral range is dependent upon the coating applied to absorb the laser power. The coating used on many thermopiles is broadband in nature and is relatively flat from the ultraviolet through the infrared. These sensors have natural response times on the order of several seconds for a low power sensor and up to one minute for a kilowatt sensor. When combined with a Coherent, meter a speed-up algorithm provides a much faster response – on the order of seconds for most sensors.

If you are measuring the power output of a CW laser with power levels from the tens of mW to kW level, or in the infrared region beyond 1800 nm (beyond the spectral limit of a Germanium photodiode sensor), a thermopile is most likely the best sensor choice. If the laser is pulsed, then the option of an energy sensor becomes available as well.

A unique capability of thermopile sensors is the ability to integrate the power of a single "long" laser pulse (long refers to pulses roughly 1 msec to up to several seconds in pulse length) over the pulse duration. The meter analyzes the output of the thermopile and applies the integration through the use of an algorithm that results in a Joules reading. This is very useful for what are commonly called long-pulse medical or industrial type lasers. This type of measurement requires careful selection of the appropriate power sensor based upon the laser pulse being measured. Coherent's laser measurement catalog provides guidelines on how to select the correct sensor for these types of applications, and customers are always welcome to contact our sales staff for help.

Coherent has two lines of thermopile sensors. The "LM Model" line utilizes a unique thermopile disk in which the thermocouples are split into four quadrants, allowing the sensors to provide beam position information in addition to power measurement. The "PM Model" line incorporates traditional thermopile disks that provide power measurement without beam position information.

Semiconductor Photodiode/Optical Sensors

Semiconductor photodiode-based sensors convert incident photons into current that can be measured by our instruments. The photodiodes used in these types of sensors offer high sensitivity and low noise, enabling them to detect very low light levels. Attenuating filters must be used when operating above the milliwatt level to avoid saturation.

Photodiodes also have a fast response time, so they are convenient for tuning and peaking lasers. The spectral range is more limited than our other sensor technologies. These devices are also referred to as optical sensors. Semiconductor/optical sensors are limited to measuring CW laser power.

These types of sensors have several orders of magnitude higher sensitivity than thermopile sensors and are quite stable. They do, however, suffer from photocurrent saturation. If the laser is in the nW to low mW range, a measurement system based upon an optical sensor is likely a great choice. If the laser output is much above the tens of mW level then you should probably lean toward a thermopile sensor, or a pyroelectric sensor if the laser is pulsed and the repetition rate is less than roughly 10 kHz.

For low power measurement of pulsed lasers, Coherent does offer several EnergyMax energy sensors based upon photodiodes (such as J-10Si-LE). These are a great alternative to the typical power type optical sensors and allow measurement of pulsed lasers down to tens of pJ (equivalent to tens of nW average power at 1 kHz).

Most manufacturers of laser measurement devices are able to measure pulsed lasers with pyroelectric sensors at up to roughly the 10 kHz level. So if you are using a pulsed laser with a repetition rate less than 10 kHz you have a choice between measuring pulse energy with a pyroelectric sensor or average power with a thermopile sensor. Lasers with repetition rates faster than this will most likely require the use of a thermopile sensor to measure the average power.

An important benefit associated with pyroelectric sensors is that the measurement response is very fast, whereas, the response from a thermopile will be much slower. For example, a measurement system based upon a pyroelectric sensor will provide a measurement within several hundred microseconds, as compared to a thermopile system that might take several seconds to achieve a stabilized measurement.

Typical Measurement Capabilities of each Sensor Type

It is often useful to understand the typical capability of each sensor type when shopping for a measurement solution. The following table outlines roughly what each type of sensor can measure. These are not meant to be considered rigid limitations as there are often certain sensor models within a particular technology that can push beyond the typical limits.

Laser Type	Measurement Needed	Power Range	Wavelength Range	Sensor Type
CW	Avg Power	10 nW to 50 mW 200 µW to >5 kW	250 nm to 1800 nm 0.15 µm to 12 µm	Optical – Power Mode Thermopile
Pulsed	Avg Power	200 µW to >5 kW	0.15 µm to 12 µm	Thermopile
Pulsed	Energy Per Pulse	100 nJ to >10J	0.15 µm to 12 µm	Pyroelectric
Pulsed	Energy Per Pulse	10 pJ to 800 nJ	325 to 1700 nm	Optical – Energy Mode
Long Pulse (>1 ms)	Single Pulse Integrated Energy	1 mJ to >300J	0.15 µm to 12 µm	Thermopile

Selecting the Right Meter

Once a sensor has been selected, meter selection consists of choosing a meter that is compatible with that sensor (i.e. making sure if a pulse energy sensor is chosen that the desired meter is also capable of measuring energy), as well as selecting a meter that provides the analysis capabilities that will be required such as statistics, data logging, or PC interfacing.

Coherent produces some meters that measure only power, some that measure only energy, and some that measure both. Power-only and energy-only meters offer simplicity and economy, but some advanced capabilities are sometimes only offered in meters that provide both power and energy measurements, so these products should be considered, even if the use is for a single measurement type.

Coherent offers a broad range of meters in terms of functionality and performance. Typically, the most important meter characteristics involved in selecting a particular model are the following:

Display Type

Meter display types include digital and analog needle type feedback.

Digital meters include fixed-segment and graphical, and can typically be read with greater precision than analog meters. Fixed-segment display meters can include tuning indicators for peaking laser output, in addition to numerals and enunciators, but do not have graphing capabilities. Graphic displays are typically found on higher performance meters and allow for full graphing and on-screen menus.

Performance

For power-only meters, the most important performance characteristic is usually the noise floor of the instrument, since this will determine the ability to make low-light level measurements and set the absolute accuracy and resolution of the device. For energy-only meters, the deciding performance characteristic is typically the maximum repetition rate. Most manufacturers carry a range of instruments. While all instruments are typically quite good, as the performance point moves up. The circuitry will contain higher resolution components in the analog-to-digital circuitry and include more complex digital signal conditioning and processing capabilities. Higher performance meters may also have higher bandwidth circuits, thus allowing faster pulsed lasers to be measured with energy sensors.

Interface Options

Computers are often used to control power/energy meters and other instruments, as well as to store and analyze acquired data. Coherent offers meters with IEEE-488 (GPIB), RS-232 and USB interfaces to enable communication with a host computer. Meters with these interfaces will include installable software that will allow the customer to control the meter remotely and acquire data on the PC without writing any custom software. Drivers are also typically provided to allow customers to write their own customized software for unique applications.

Analysis Capabilities

Some meters have built in capabilities for logging data and performing various statistical calculations on stored entries, averaging and wavelength correction. More sophisticated energy meters can provide values for irradiance, fluence, ratiometric calculations and other parameters. This can be an important feature if the customer wants to perform an analysis on a data set and quickly record a statistical result without going to the trouble to import the data into a spreadsheet program on a PC later.

Other Meter Considerations

There are a number of other applications related factors that may be important when selecting a measurement system. For example, physical size is a consideration in meters for use by field service personnel; Coherent makes a number of hand held meters for these uses. Some meters offer extensive programmability, and can be configured for simplified use by production line personnel (e.g. go/no go reading), or interfaced with other test equipment.

Shown to the left are a few examples of laser power and energy meters ranging from a basic FieldMate meter that only measures laser power, to a FieldMaxII meter that allows power and energy to be measured and adds statistics and USB interfacing, to a more advanced data analysis platform based upon the LabMax meter that works with all sensors and contains numerous PC interfacing options.

Calibration

Most laser power and energy sensors and meters sold on the market are calibrated and traceable to a national standards laboratory and are sold with a traceable calibration certificate. In the case of Coherent, our meters and sensors are calibrated against NIST-traceable working standard sensors which are, in turn, calibrated against NIST-calibrated golden standard sensors. These working and golden standards are maintained with the utmost care, recalibrated annually, and verified even more regularly. We maintain multiple NIST-calibrated standards at many laser wavelengths to support the growing calibration needs of our customers.

Optical calibration is a core competency at Coherent and we strive to continually improve our methods, precision, and repeatability. Additionally, most of the calibrations are performed with highly automated systems, thus reducing the possibility of human error. We also strive to deliver the best service in the industry, with a knowledgeable and responsive staff, and rapid turnaround.

As the largest laser manufacturer in the world, Coherent has been able to build state-of-the-art calibration facilities containing the widest possible range of laser types and technologies. This enables us to perform instrument and sensor calibration under many combinations of wavelength, power, and operating characteristics.

Summary

Purchasing a laser measurement system begins with a detailed review of the laser (or lasers) needing to be measured:

- Have several key laser parameters readily available: Wavelength, minimum and maximum average power, and beam size.
- If the laser is a pulsed laser, you will need to know the laser pulse width, repetition rate, and minimum and maximum pulse energy. If the repetition rate is adjustable it will be useful to know the maximum repetition rate at maximum energy, hence resulting in a maximum average power number. This will help determine how much heat sinking will be required if a pyroelectric energy sensor system is chosen.

The following guidelines can be considered when determining what type of measurement technology is a good fit for your laser system:

- If the laser is pulsed and the repetition rate that needs to be measured is less than roughly 10 kHz, a pyroelectric sensor becomes a good option. If the laser is higher than 10 kHz, in most cases a thermopile sensor will likely need to be used.
- Even if a laser is pulsed, a thermopile sensor can still be used to measure average power. This is a choice that is often dependent upon the budget because pyroelectric energy measurement systems are typically more expensive than a power meter system.
- If the power or energy levels are very low, and the wavelength is not further into the infrared than 1800 nm, a sensor based upon a semiconductor photodiode often becomes a good choice due to their ability to respond to very low light levels. Coherent makes CW power sensors and pulsed energy sensors based upon this technology.
- If the laser power measurement is much above the 300W level a water-cooled sensor is going to be required. At these power levels you will need to plan ahead to have a chiller or water line available to cool the sensor.

After a sensor is chosen, a compatible meter must be chosen to complete the measurement system. The meter samples the signal from the sensor and converts it from an analog to a digital signal. The meter employs digital signal processing and other correction algorithms, such as wavelength compensation and temperature compensation, to provide an accurate, NIST-traceable laser power or energy measurement. Customers may choose between several different meter models that range from basic meters that only display the final reading on an LCD, to more advanced meters that can perform statistical analysis, log data, or connect to a PC for completely hands-free remote operation.