HIGH-POWER DIODE LASER ARRAY METROLOGY[*]

Paper #409

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Abstract

NIST has been tasked by DARPA to provide wall plug efficiency and spectral measurements of high-power high-efficiency laser diodes and arrays for DARPA's Super High Efficiency Diode Sources (SHEDS) program. To meet the needs for this project, the Optoelectronics Division has developed a new laboratory at NIST to measure electrical power, optical power, wavelength and line width, and junction temperature for lasers supplied by project participants. We describe a novel flowing-water optical power meter (FWOPM) that we have developed to meet the unique optical power measurement challenges presented by these lasers. We have also developed a new method for determining the average laser junction temperature through a simple model of laser waste heat as a function of drive current and cooling temperature. In addition, we present a preliminary uncertainty analysis that yields ~ 1 % uncertainty (with a confidence interval of 95 %) for the efficiency measurements. We intend to continue offering these measurements as part of the NIST Calibration Services for optical radiation measurements, which are available to anyone for a fee.

Introduction

NIST has had a long history of support for high power laser metrology [1, 2]. In the 1970's NIST developed laser calorimeters [3] designed to measure laser power up to 1 kW (300 J), and has maintained calibration services [4] since that time at 10.6 μm and 1064 nm based on these standards. In addition, a water-cooled high power laser calorimeter [5, 6] capable of measurements up to 100 kW (1 MJ) was designed and built to support Department of Defense laser programs.

We are participating in the DARPA SHEDS project to provide the fundamental metrology to accurately assess the performance of devices produced by the project participants. The requirements for Phase I of the SHEDS Project are to demonstrate at least 65 % wall-plug efficiency at 80 W of optical power and 50 °C junction temperature. There is an additional spectral requirement for full width at half maximum (FWHM) the array to be less than 4.5 nm.

These lasers present significant new measurement challenges. Edge emitters have a large divergence on the fast axis, which makes it difficult to capture the entire beam. Along with the high optical power levels being routinely produced and the relatively larger size of the arrays, achieving accurate measurements does present a challenge for the best commercially available optical radiometers. We have developed a novel optical power meter that enables accurate measurements of these lasers, eliminating the problems encountered with commercial laser radiometers.

Laser junction temperature is routinely determined by the manufacturers through modeling or with measurements using current pulses of low duty cycle to reduce average waste heat in the laser. Because of the very large variety of packaging configurations encountered in this project, the current pulse method is difficult to implement. We describe a method that uses a simple linear model for the wavelength temperature dependence and the thermal conductivity of the package, which is fit to data of the wavelength as a function of the DC current and cooling-water temperature.

We will now describe the measurement system and procedures including the new FWOPM, the junction temperature measurements, and the uncertainties for the efficiency measurements.

Measurements

General Setup

The measurements are performed on a standard optical table inside an enclosure equipped with a high

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efficiency particulate air (HEPA) filter. The enclosure has an opening at the bottom of each side wall to allow for the laminar flow of filtered air across the table surface. This provides for a clean zone above the optical table to keep the laser packages free from dust during testing and storage.

The data acquisition system consists of a computer and voltmeter with multichannel scanning capability. The computer is used to control the power supplies and voltmeter through a GPIB interface with custom software. The power supplies used are 2 kW variable output general laboratory supplies with maximum outputs of 8 V/ 220 A and 20 V/ 100 A. These power supplies provide essential flexibility through customized software for testing a large variety of laser array types. This enables programming of custom startup and ramping of voltages and currents according to manufacturer specifications. Conventional (analog) diode laser drivers are generally not capable of handling a wide variety of electrical power requirements.

Generally, heat removal for the optical power and waste heat generated in the lasers is handled by a process cooling loop at 10 °C. The process water is available for chillers that require water cooling and is used in the fan coils for the room AC to remove heat generated by air cooled chillers.

Laser Diode Measurement Setup

The laser diodes were measured for electrical power input and optical power output, with the ratio being defined as the "wall plug" efficiency. Figure 1 shows a diagram of the measurement setup.

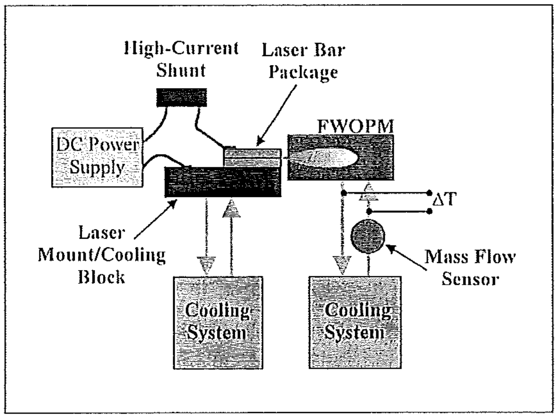

Figure 1: Laser diode array measurement system diagram.

The laser diode array package supplied by the manufacturer is normally mechanically mounted on an insulated adapter plate that is in turn attached to a kinematic mounting plate supported by an optical post. The adapter plate aids in supplying electrical current and cooling water to the laser package. Generally, each laser manufacturer uses some proprietary mounting scheme requiring a customized mounting arrangement. However, most configurations for mounting of laser packages can be accommodated with standard optical mounting hardware.

The power supply is used to provide power to the laser package through a calibrated high-current shunt to measure current. The voltage across the laser package is measured at appropriate points as close to the active elements as possible. The electrical power applied to the laser package $P_{\text{Electrical}}$ is calculated with the equation

$$P_{\text{Electrical}} = I \cdot \left(V_{\text{Laser}} - I \cdot R_{\text{Series}}\right), \quad (1)$$

where I is the current measured with the shunt, V_{Laser} is the voltage measured on the laser package, and R_{Series} is a correction for the series resistance of the laser package. The series resistance is measured (when possible) with a special package (supplied by the manufacturer) that has the laser bar removed and is shorted internally. The shorted package is measured the same way as the laser package (i.e., with the same voltage pickoff points) to ensure accurate correction for the package series resistance.

The cooling system for the laser package is supplied by a deionized water compatible chiller with a water-to-water heat exchanger. House chilled water is used to supply the chiller with 10 °C process water. An auxiliary heat exchanger at the chiller output that uses a compressor refrigerated water bath can be used to provide fine temperature control of the cooling water to the laser package. This "two loop" system can provide cooling water at up to 10 l/min at 2 bar with 0.05 °C temperature stability.

Optical Power Measurements

We initially encountered difficulties when attempting to measure the optical power from edge-emitting laser diodes by the use of commercial laser power meters. In order to capture the large divergence beams from the diode arrays, the radiometer must be very close to the array. Unfortunately with disk-type thermopile radiometers of large area, this close proximity can disrupt the thermal equilibrium of the absorber disk, which distorts the temperature measured with the thermopile. This error is in addition to errors caused by any spatial non-uniformity of the responsivity of the radiometer. In addition, most high-power radiometer coatings reflect a significant portion of the incoming radiation, which was not accounted for when the radiometer was calibrated. When used in this type of measurement, a significant portion of this radiation may be reflected back to the radiometer by the laser mounting hardware, effectively increasing the collection efficiency of the radiometer. Another type of laser radiometer use in the industry is integrating-sphere based radiometers, which are notoriously sensitive to port conditions. Again, since the laser diode or diode array being measured must be placed directly in the input port, complicated corrections must be applied to correct for these sphere loading effects.

Consequently we have developed a flowing water optical power meter (FWOPM) based on measuring the temperature increase of water cooling the detector as shown in Figure 2. Several laser power meter manufacturers have produced these types of power meters in the past so the technique is not new.

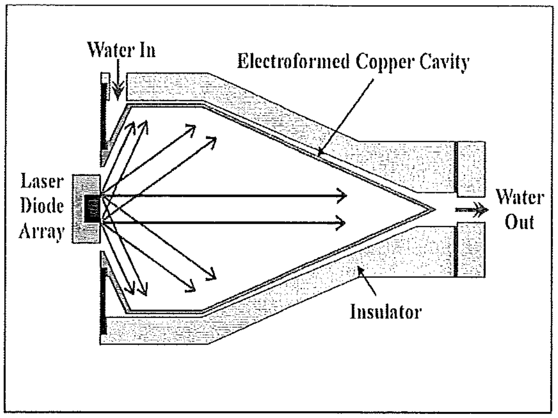

Figure 2: A diagram of the flowing water optical power meter (FWOPM) for diverging beams.

A thin-walled copper cavity that has a metallic diffuse-reflecting black coating [7] on the inside captures and converts the laser output to heat. The cavity is cooled with water flowing on the outer surface of the cavity. The optical power $P_{Optical}$ is then provided by the equation,

$$P_{Optical} = \rho_m \cdot \Delta T \cdot C_p \qquad (2)$$

where ΔT is the temperature difference between the input and the output water, ρ_m is the water mass flow rate, and C_p is the heat capacity of the water. The input and output water temperatures are measured with calibrated thermistors, and the mass flow rate with a high-accuracy (Coriolis type) mass-flow meter. Figure 3 shows a typical data series where the laser array is cycled on and off to eliminate baseline temperature drifts. The cooling system for the FWOPM is a single loop with a refrigerated chiller and stainless steel tank that gives a temperature stability of better than 0.01 °C.

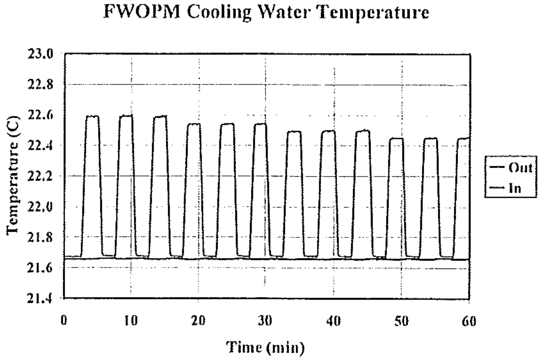

Figure 3: Typical time series for the input and output temperature of the water cooling the FWOPM.

The system is calibrated by substituting an electrical heater for the optical head. The electrical heater is well insulated from the environment, and provides for a direct calibration of the thermistors and flow meter over a wide range of applied power and water flow rates. The optical measurements are traceable to SI units through the same calibrated shunt and voltmeter used in the electrical measurements.

This type of detector loses very little heat to the environment, since the ΔT value for the cooling water is typically less than one °C. As a rule of thumb, an increase of one °C of water temperature at one liter per minute of flow corresponds to ~ 70 W of power. The heat lost by the FWOPM to the environment was tested by measuring the optical power from a laser diode at ~ 90 W while varying the flow rate in the FWOPM. The measured optical power did not vary by more than 0.2 %, which is less than the typical statistical variation for the FWOPM measurements at this power.

This cavity was designed to collect nearly 2π steradians of the laser output and absorb 99.9 % of the optical radiation, so that very little radiation is reflected back onto the laser array. These assumptions were tested by comparing a prototype FWOPM to a commercial thermopile using a *collimated* laser beam up to 25 W. The thermopile was calibrated in the NIST high power calibration services laboratory [4]. The agreement of the thermopile and the FWOPM was within the uncertainty of the comparison, which is ~ 1.0 % (with a coverage factor K = 2, which corresponds to a confidence interval of 95 %). The cavity collection efficiency was also tested (on a prototype) as a function of the optical beam input angle: the cavity absorbs greater than 99 % of the input beam up to 60 degrees from normal incidence.

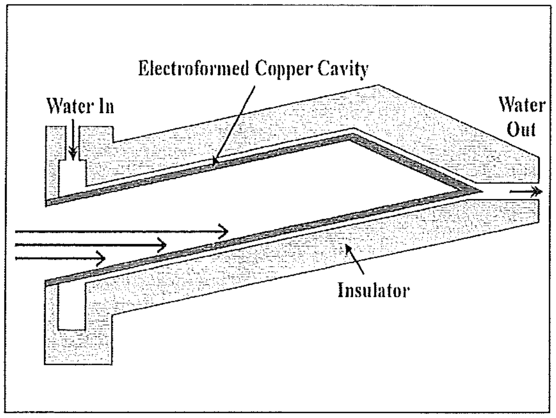

Figure 4: A diagram of a potential design for a FWOPM for collimated high-power laser beams.

The cavity shown in Figure 2 is specifically designed for highly diverging beams, but is not optimum for collimated high-power lasers. The diffuse absorber can be damaged by the higher energy density of collimated beams. An alternative design shown in Figure 4 could be used where the laser strikes the inside wall at a grazing angle with a specularly reflecting surface. Also, by choosing a large wall reflectance the energy density on the cavity wall can be reduced while still fully absorbing the laser beam through multiple reflections in the cavity. The various FWOPM heads could be designed to allow for easy swapping into the FWOPM measurement system through quick-connect fittings.

Spectral Measurements

Spectral measurements are performed with a commercial 10 cm diameter gold coated integrating sphere as the receiver. A water-cooled sphere of 25 cm diameter is also available for measurements above 100 W. A fiber bundle is used to pipe the laser radiation to a commercial CCD array spectrometer with a spectral resolution of 0.1 nm.

Results

General Procedure

Measurements are normally performed at a fixed laser cooling water temperature. Data are acquired as a function of time with the laser alternately off and on to determine baseline values for the FWOPM. The current supplied to the laser array is ramped up and down according to manufacturer's requirements. The input and output temperature of the water flowing in the FWOPM, the voltage on the laser package, and the voltage on the shunt are measured at fixed time intervals. From these data and the above equations the electrical and optical power are calculated. Typical laser array efficiency results as calculated from the ratio of the optical and the electrical power are shown in Figure 5.

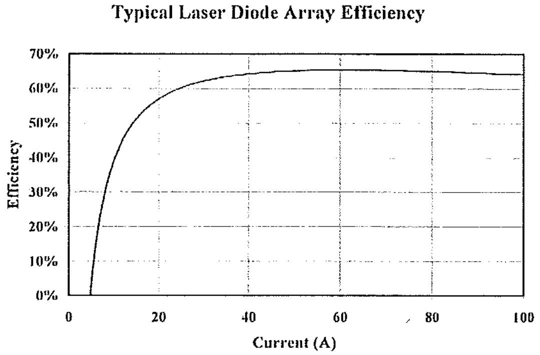

Figure 5: Typical "wall plug" efficiency as a function of applied electrical current.

Junction Temperature Determination

The method for determining the laser array average junction temperature relies on the measurement of electrical input power, optical output power, and centroid wavelength of the laser diode array over a range of drive current and cooling water temperature settings. Figure 6 shows typical data of several data sets where for each set the cooling temperature is held fixed while the electrical current is varied. This analysis assumes that the centroid wavelength λ_C is a linear function of junction temperature T_J

$$\lambda_C = M \cdot T_J + \lambda_0, \quad (3)$$

where M is the temperature dependence of the centroid wavelength, and λ_0 is the wavelength at 0 °C. The junction temperature is in turn a linear function of the thermal (waste) power P_W dissipated in the laser package, and is given by

$$T_J = R \cdot P_W + T_0. \quad (4)$$

The reference temperature T_0 is usually the input cooling water temperature and R is then the thermal impedance of the laser package. The waste power is determined by subtracting the measured optical power from the electrical input power.

Substituting equation (4) into equation (3), thus eliminating T_J, gives an equation for the centroid wavelength λ_C as a function of thermal power P_W and the reference temperature T_0. This equation can be fit to the measured values to determine R, M, and λ_0. The thermal impedance R is then used to calculate the cooling water temperature needed to produce the desired junction temperature at a given drive current.

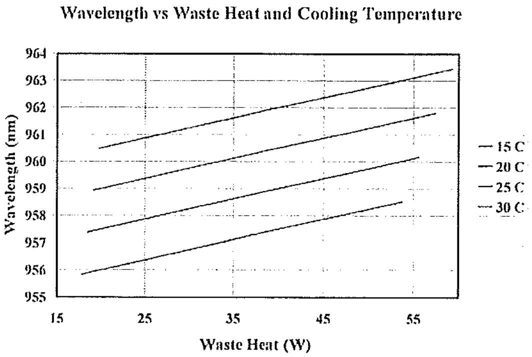

Figure 6: Graph illustrating typical measurements for determining device junction temperature. Center wavelength and waste heat were measured at various current and cooling water temperatures.

The accuracy of this method is clearly dependent on the package configuration. The method seems more consistent when the laser package uses microchannel cooling and the input cooling water temperature is used as the reference T_0. When we attempted this measurement for a package that had a thermoelectric cooler between the laser and the cooling water, and used for the reference T_0 the temperature measured with a thermistor at a point near the laser, the results were not consistent with expected values for M and K. A full uncertainty analysis for this method has not been completed, but we expect that the uncertainty of T_J will be lower than ± 2 °C for most laser package configurations.

Uncertainty Assessment

The uncertainty estimates for the NIST laser energy measurements are assessed following guidelines given in NIST Technical Note 1297 [8]. To establish the uncertainty limits, the error sources are separated into (1) Type B errors, whose magnitudes are determined by subjective judgment or other nonstatistical methods, and (2) Type A errors, whose magnitudes are obtained statistically from a series of measurements.

All the Type B error components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm\,\delta_i$, and zero probability of being outside that region). If the distribution is rectangular, an approximation to the standard deviation, σ_s, for each Type B error component is equal to $\delta_i/3^{1/2}$ and the total "standard deviation" is approximated by $(\Sigma\sigma_s^2)^{1/2}$, where the summation is performed over all Type B error components.

The Type A errors are assumed to be independent and normally distributed and consequently the standard deviation, Sr, for each component is

$$S_r = \sqrt{\frac{\sum x^2 \frac{(\sum x)^2}{N}}{N-1}}\ , \qquad (5)$$

where the x values represent the independent measurements and N is the number of measurements used for a particular random error component. The standard deviation of the mean is $S_r/N^{1/2}$, and the total standard deviation of the mean is $[\Sigma(S_r^2/N)]^{1/2}$, where the summation is carried out for all the random error components.

The total uncertainty is determined by combining the random and systematic "standard deviations" in quadrature and multiplying this result by a coverage factor of 2. The total uncertainty, U, is then

$$U = 2\sqrt{\sum \sigma_s^2 + \sum \frac{S_r^2}{N}}\ . \qquad (6)$$

Typical values used to calculate the NIST total uncertainty for high-power laser diode array measurements are listed in Table I.

A more complete discussion of the uncertainties associated with the FWOPM will be available in a future publication.

Table I NIST Measurement Uncertainties

Source	Type B	Type A	
	δ_i	S_r	N
FWOPM calibration			
Standard resistor	0.05 %		
Electrical power	0.05 %	0.01 %	3
Thermal power		0.30 %	3
Lead heating	0.20 %		
Efficiency measurements			
Electrical power	0.50 %	0.10 %	3
Optical power		0.30 %	3
Heat lost to environment	0.20 %		
Cavity absorption	0.50 %		
Relative Expanded Uncertainty (K=2)		1.02 %	

Conclusion

We have discussed the development at NIST of a new capability to measure the "wall plug" efficiency of high-power laser diode arrays as part of the DARPA SHEDS project. To achieve repeatable results, we have developed a high-power laser standard traceable to SI units that is based on water cooling of an optical absorbing cavity. We have successfully demonstrated electrical to optical efficiency measurements with 1 % expanded uncertainty, measured spectral line position and width, and developed a technique for determining the average junction temperature of the arrays.

References

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Meet The Authors

Dr. Cromer is the project leader for the Laser Pulse Radiometry Project in the NIST Optoelectronics Division. He received his B.S. degree in physics from Rochester Institute of Technology in 1978 and his Ph.D. degree in physics from the University of Southern California in 1983. He then joined NIST (then NBS) as a NRC/NBS Postdoctoral Research Associate working in vacuum UV spectroscopy. His research areas now include measurement methods and high accuracy standards for characterizing pulsed and CW lasers. (cromer@boulder.nist.gov)

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